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# **Three-Dimensional Simulation Of River Flood Flows**

**Volume II: Figures**

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(Eng. ESTP Paris, M.Sc.)**

**Thesis submitted for the degree of  
Doctor of Philosophy  
in the department of Civil Engineering,  
The University of Glasgow**

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**June 2001**

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## **Conventions**

The following conventions are used consistently in the following thesis:

- Cross-sectional figures are plotted looking in the downstream direction.
- Velocity figures display the velocity magnitude or norm, calculated as the square root of the three spatial components of the velocity elevated to the power of 2.
- Angle plots refer to the direction of the velocity vector in the horizontal plane, with respect to the normal to the cross-section (which represents the  $0^\circ$ ). Positive angles are measured when the velocity direction is heading towards the left with respect to the normal ( $0^\circ$ ), and the value of the angle is that between the velocity direction and the normal. When the velocity is heading towards the right hand side, this is considered a negative angle and measured using the same convention. These were the conventions used by the FCF experimentalists.
- All units are SI units unless stated otherwise.

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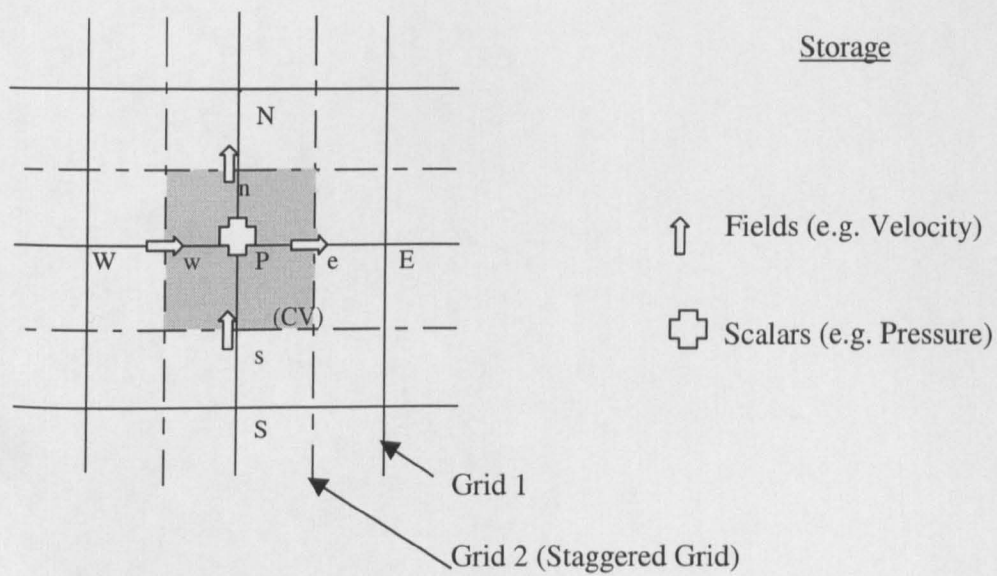
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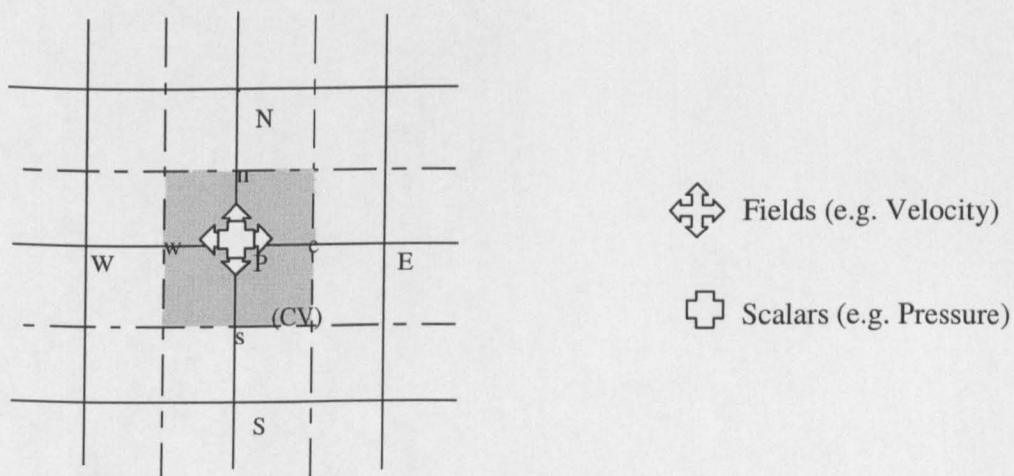


# **Chapter 4: Grids, Boundary Conditions, Solution Techniques and other Numerical Issues**

**Figures for Chapter 4**

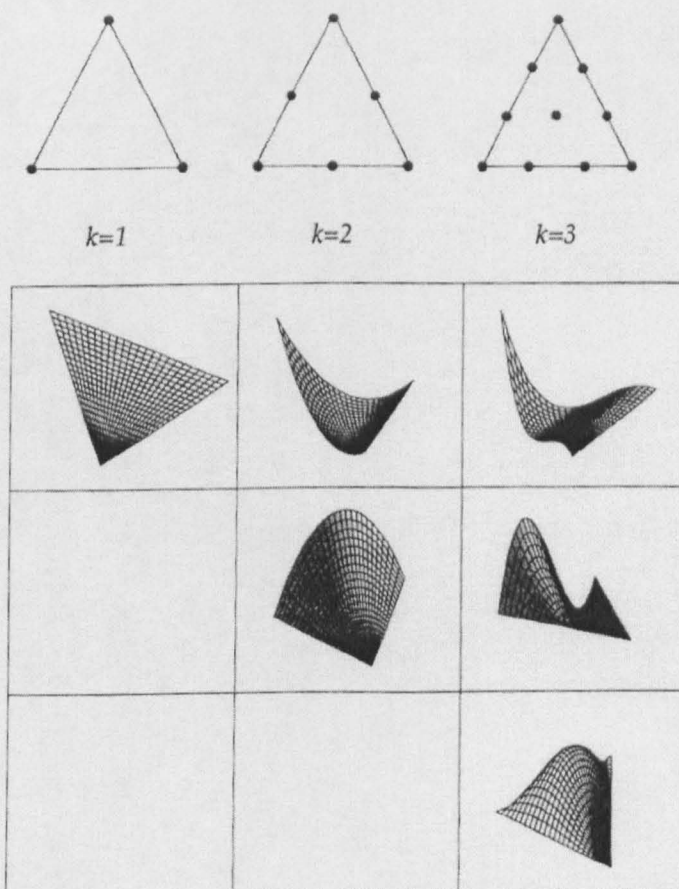


(a)

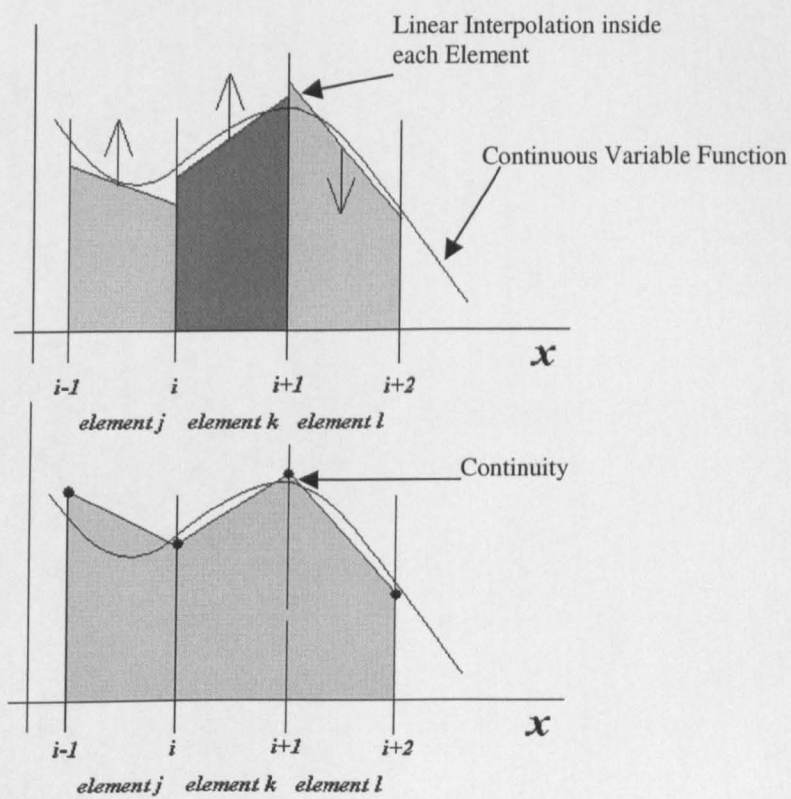


(b)

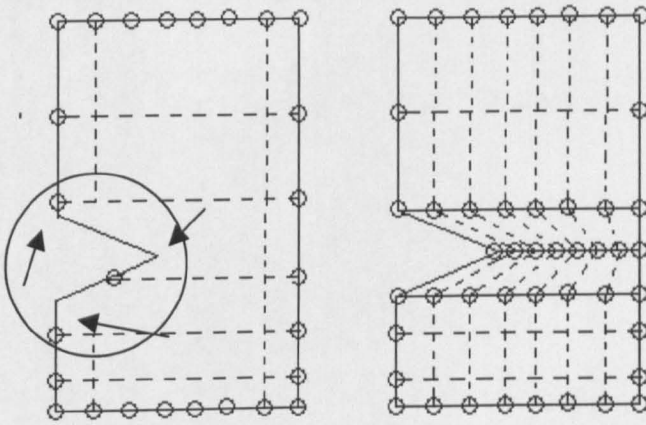
**Fig. 4.1 – Finite Volume Grids: (a) Staggered Grid, (b) Non-Staggered Grid**



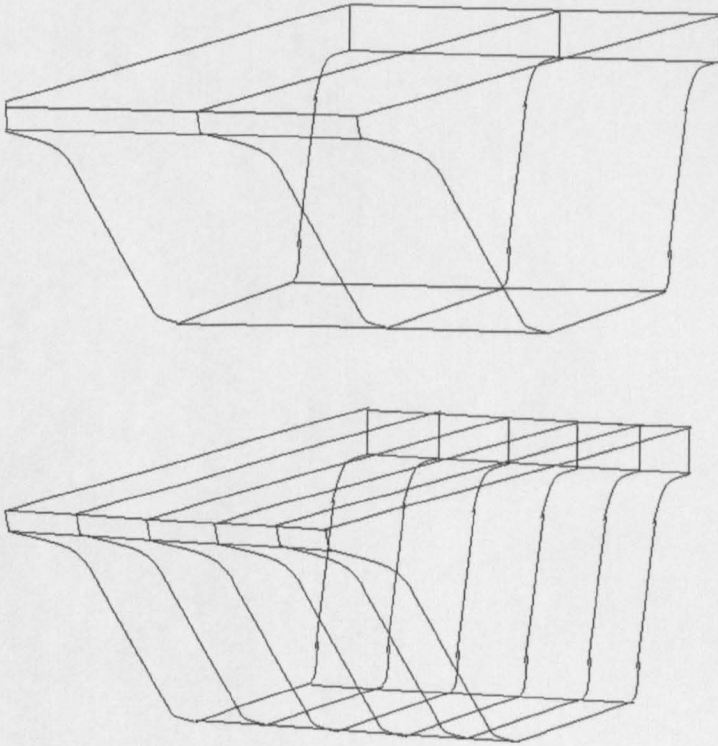
**Fig. 4.2 – Shape Functions: Linear, Parabolic and Cubic  
(After Quarteroni and Valli, 1994)**



**Fig. 4.3 – Illustration of A Finite Element Approximation**



**Fig. 4.4 – Multiblock Geometry and Meshing**

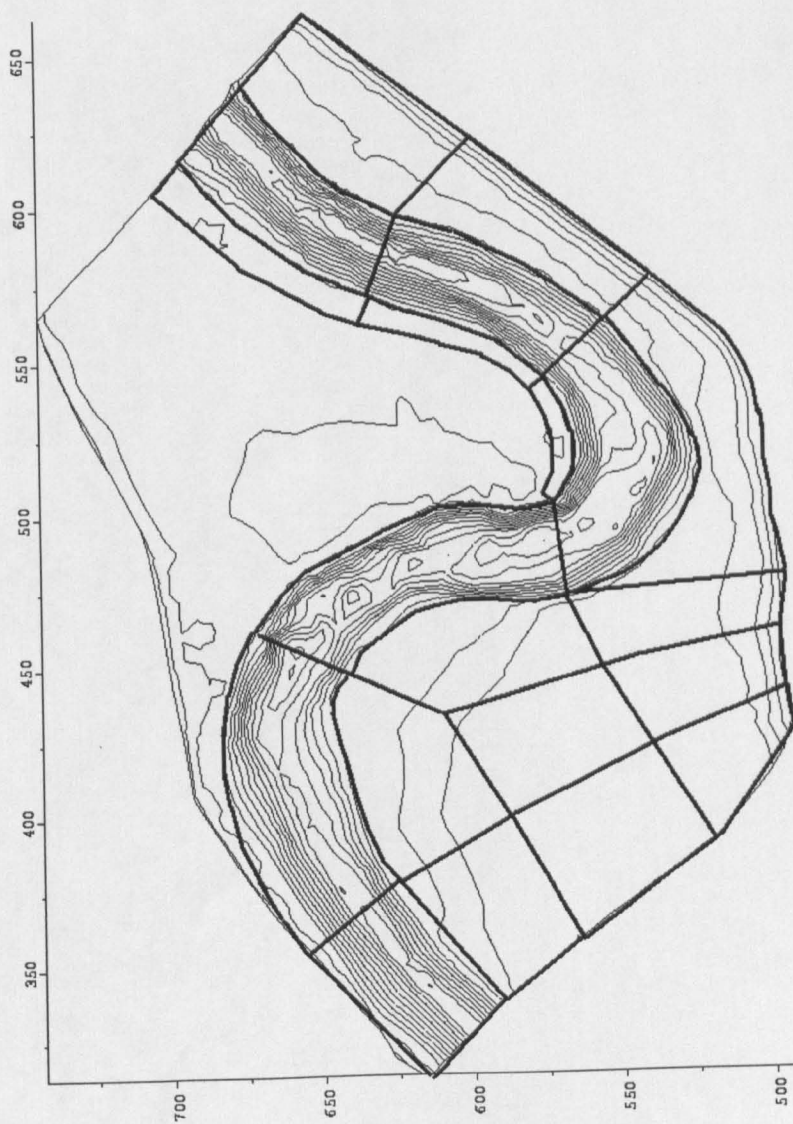


**Fig. 4.5 - Three-Dimensional Geometrical Representation of a Channel:**

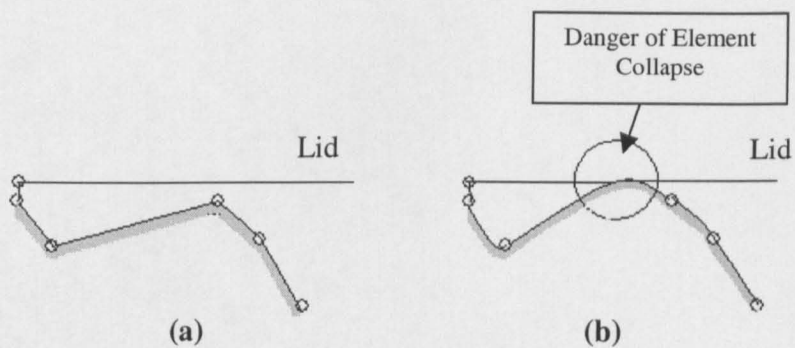
**(a) Two-Solid Representation,**

**(b) Five-Solid Representation.**



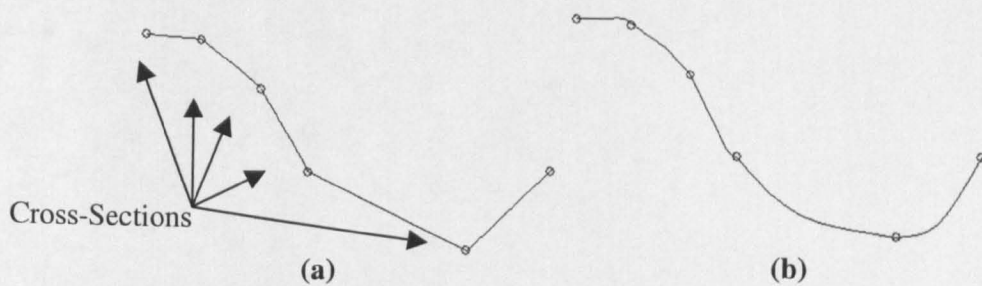


**Fig. 4.6 – Severn Plan View Multi-Block Structure  
for CFX Mesh Generation**



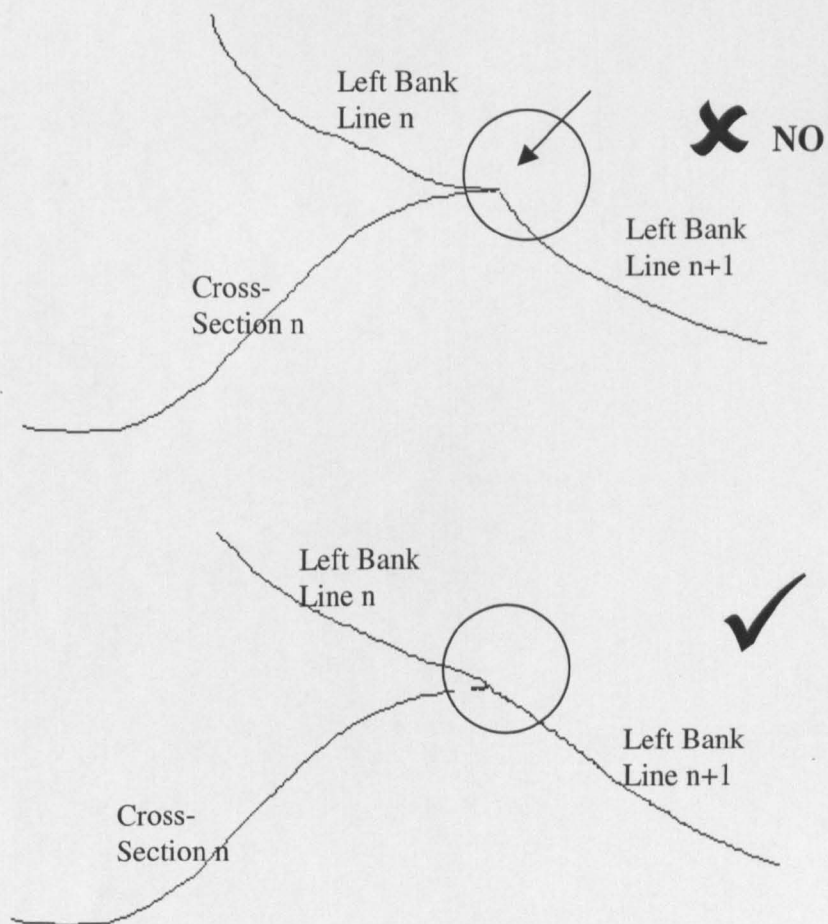
**Fig. 4.7 – Cross-Sectional Representation of the Bottom Topography**

- (a) Composite Edge made of Linear Interpolation;
- (b) Quadratic Interpolation or Spline.

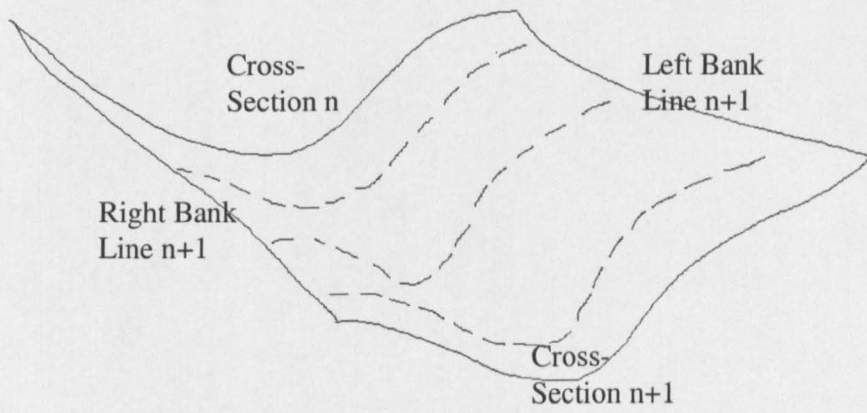


**Fig. 4.8 – Plan View Representation of a Meander: (a) Linear, (b) Spline.**

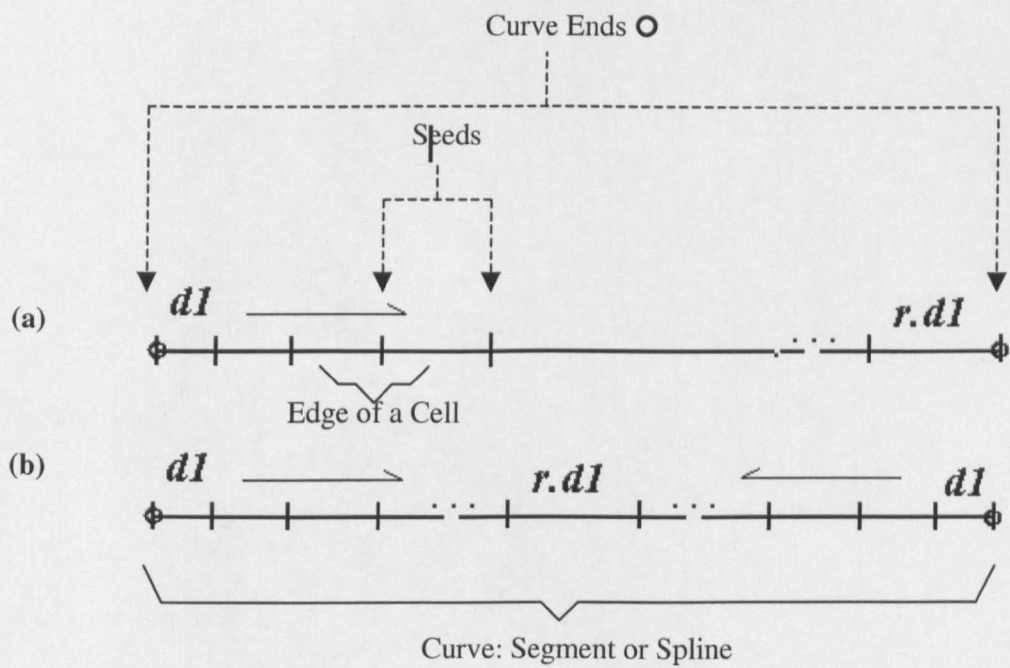




**Fig. 4.9 –Bank Line Inter-Block Connection in CFX**



**Fig. 4.10 – Bed Surface for a Natural Channel Block in CFX**



**Fig. 4.11 – Mesh Point Generation along a Curve in CFX:**  
 (a) one-directional, (b) bi-directional

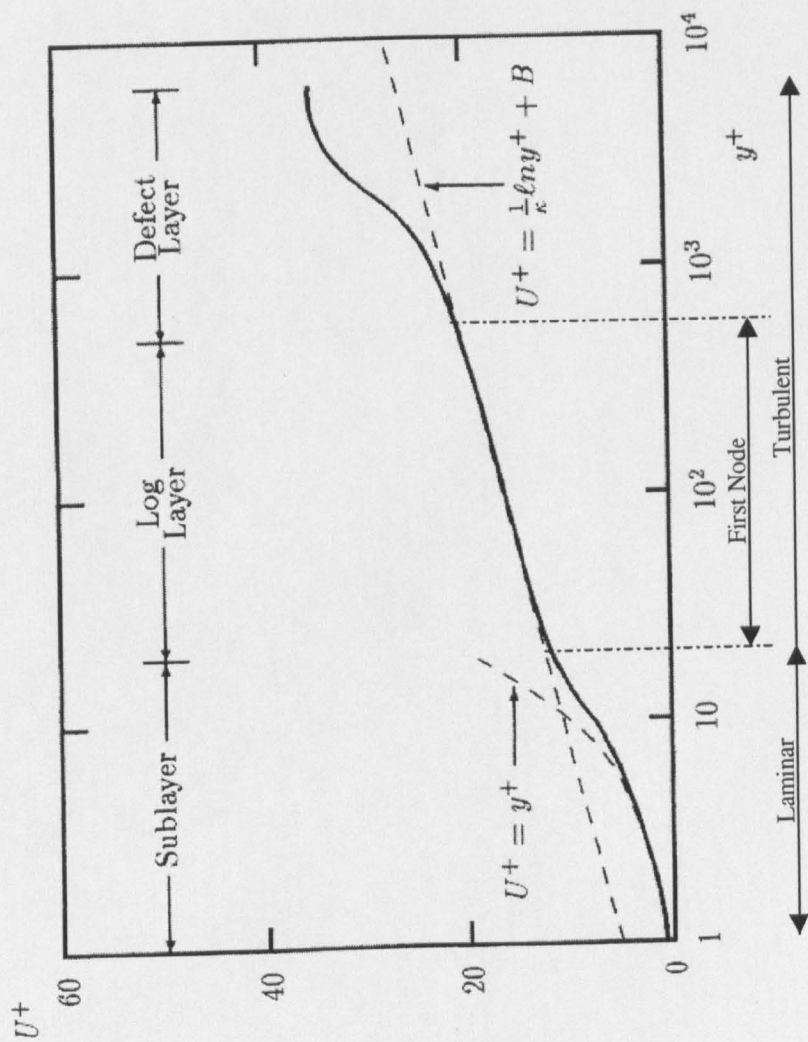


Fig. 4.12 –Velocity Profile for a Turbulent Boundary Layer  
(adapted from Wilcox, 1993)

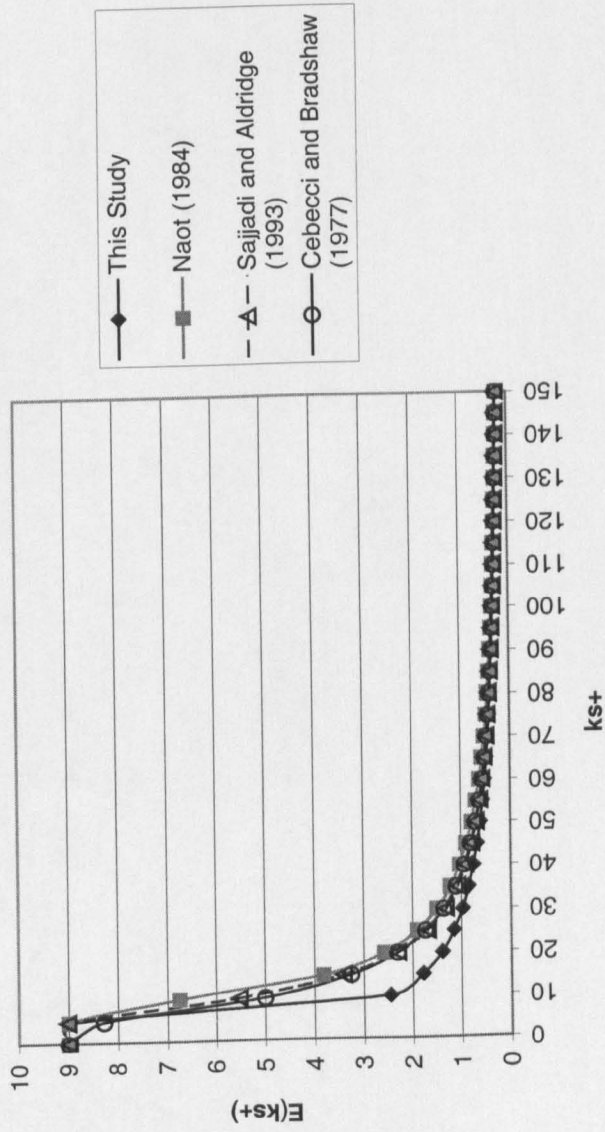
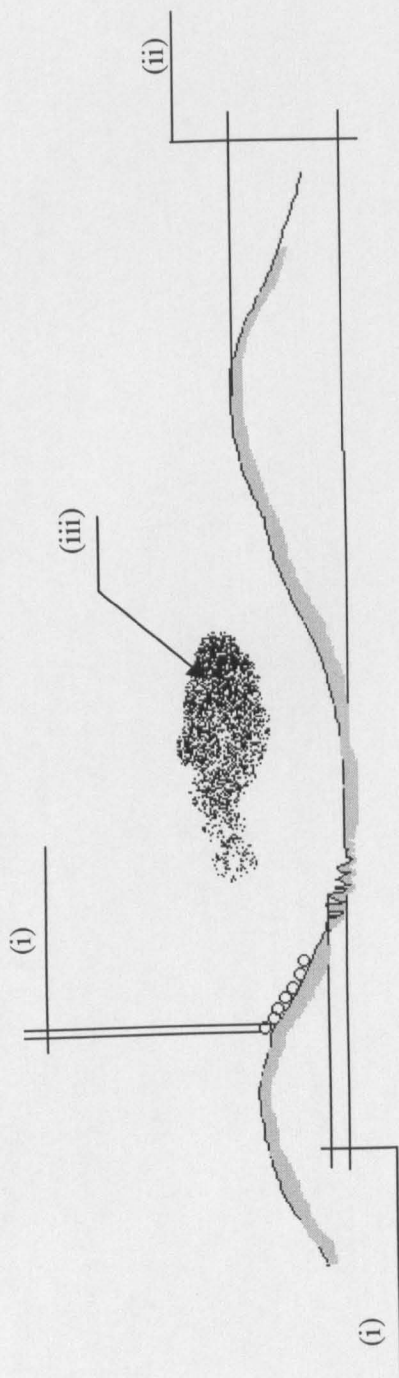


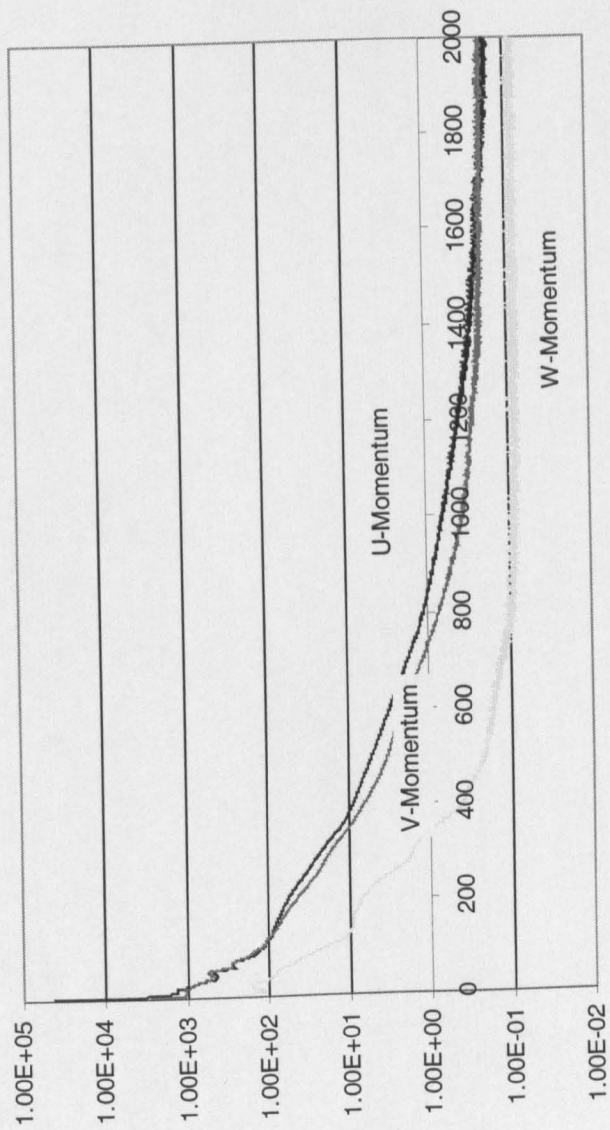
Fig. 4.13 – Law of the Wall  $E$  Value as a Function of the Non-dimensional Roughness



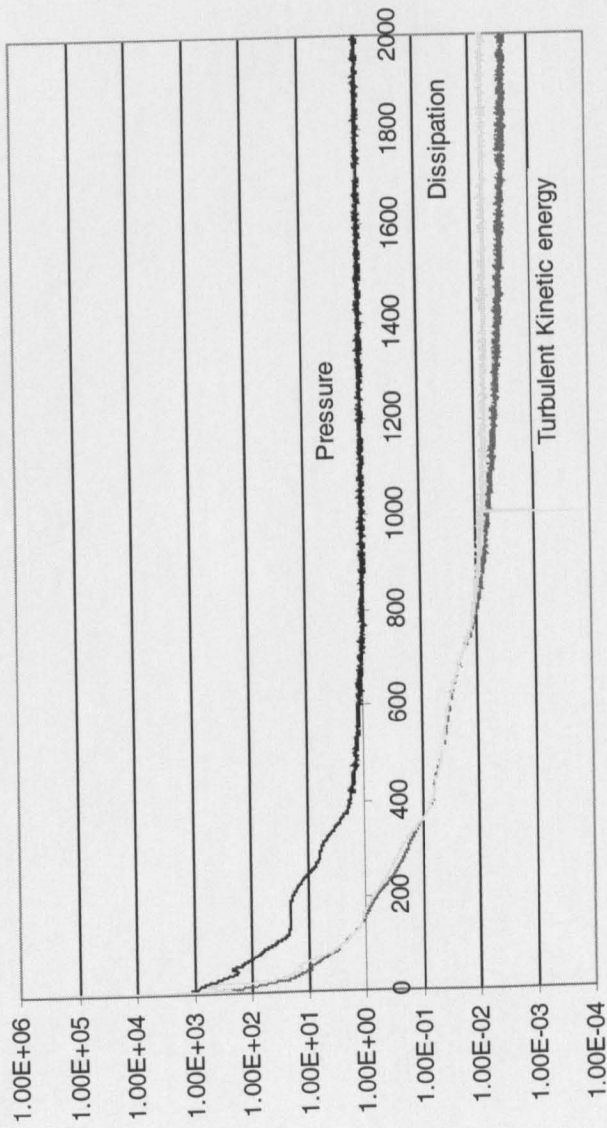
F.S.



4.14 – Parameters Influencing Roughness Height at the Walls:  
(i) Grain Roughness, (ii) Bedform Roughness, and (iii) Suspended Particle Roughness

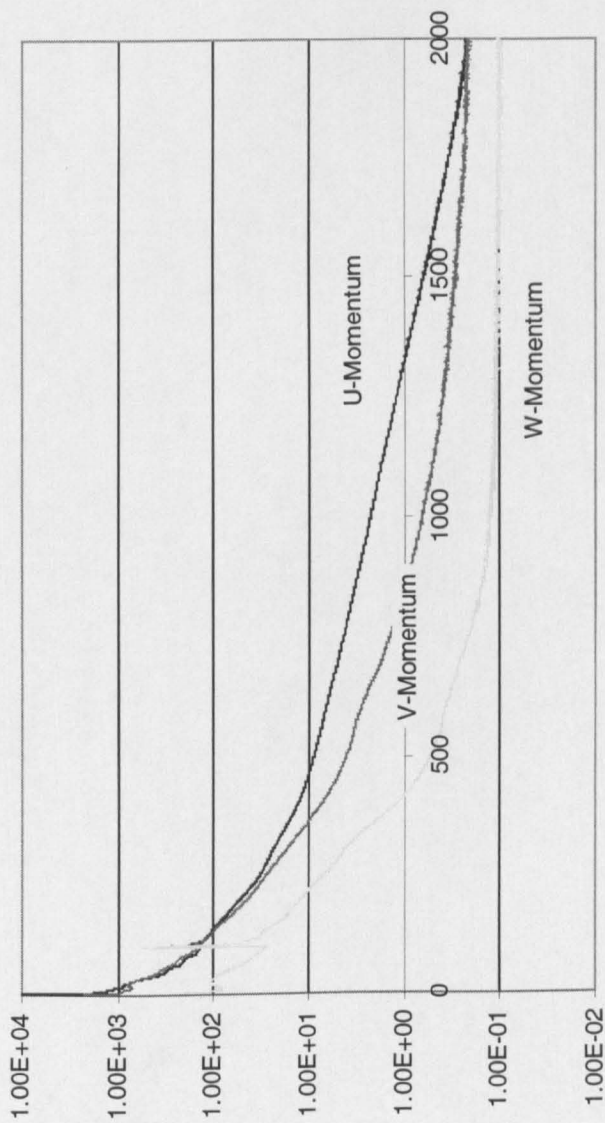


**Fig. 4.15 - Convergence History**  
(FCF Model, Grid FCF-3, K-Epsilon Model,  $ks = 0.2$  mm)

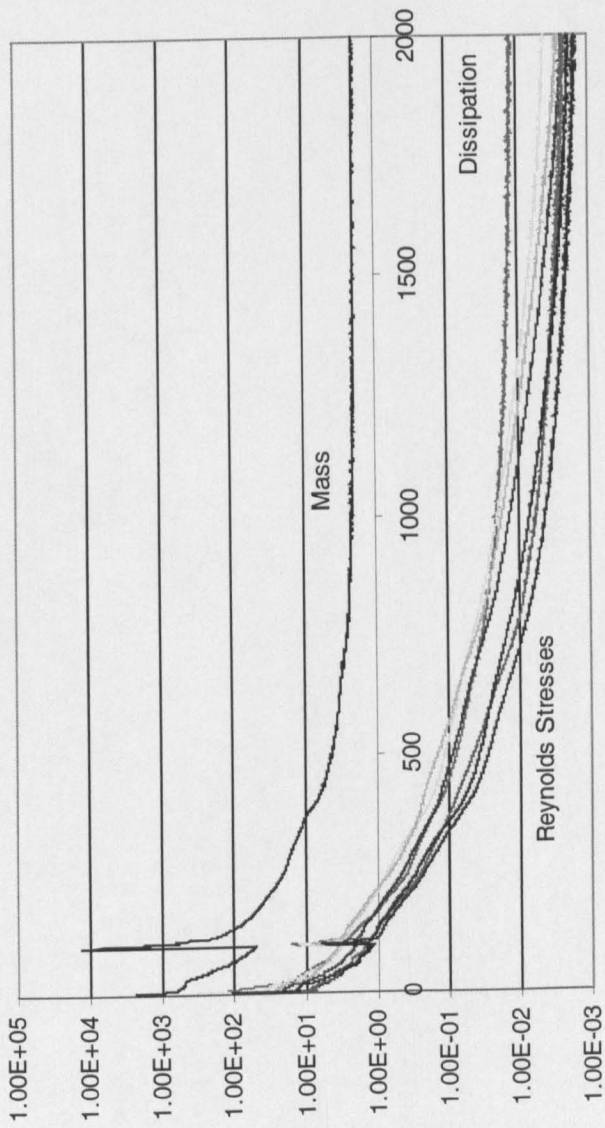


**Fig. 4.16 - Convergence History**  
(FCF Model, Grid FCF-3, K-Epsilon Model,  $ks = 0.2$  mm)

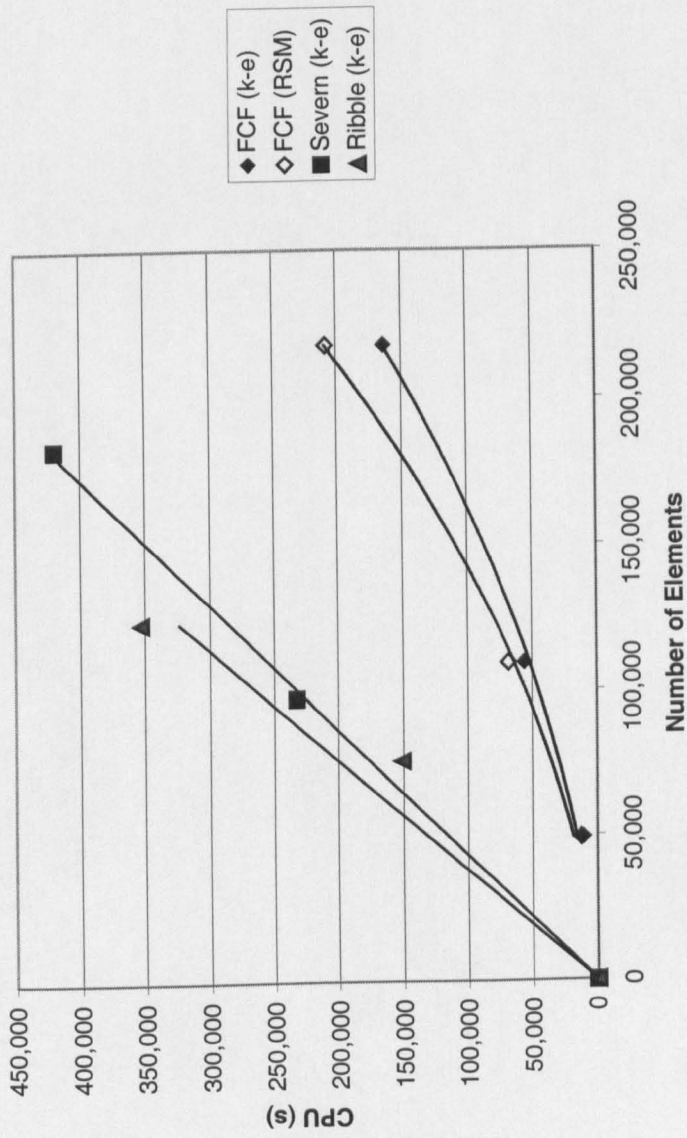




**Fig. 4.17 - Convergence History**  
(FCF Model, Grid FCF-3, RSM,  $k_s = 0.8$  mm)



**Fig. 4.18 - Convergence History**  
(FCF Model, Grid FCF-3, RSM,  $k_s = 0.8$  mm)



**Fig. 4.19 – Scalability of CFX 4.2 for FCF Experiment B23 and River Applications**

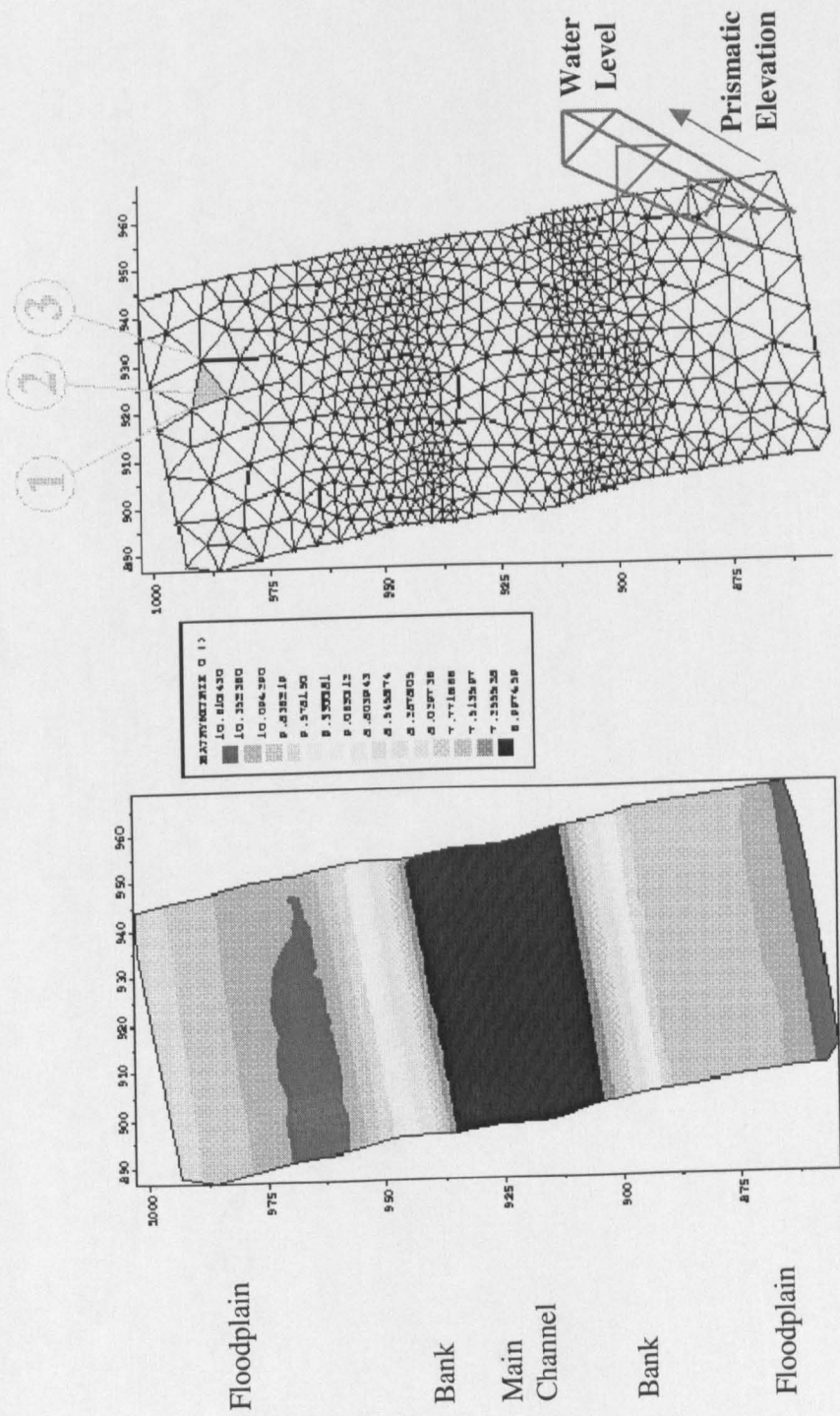


Fig. 4.20 – Topographical Representation and Mesh for a Channel Section in TELEMAC



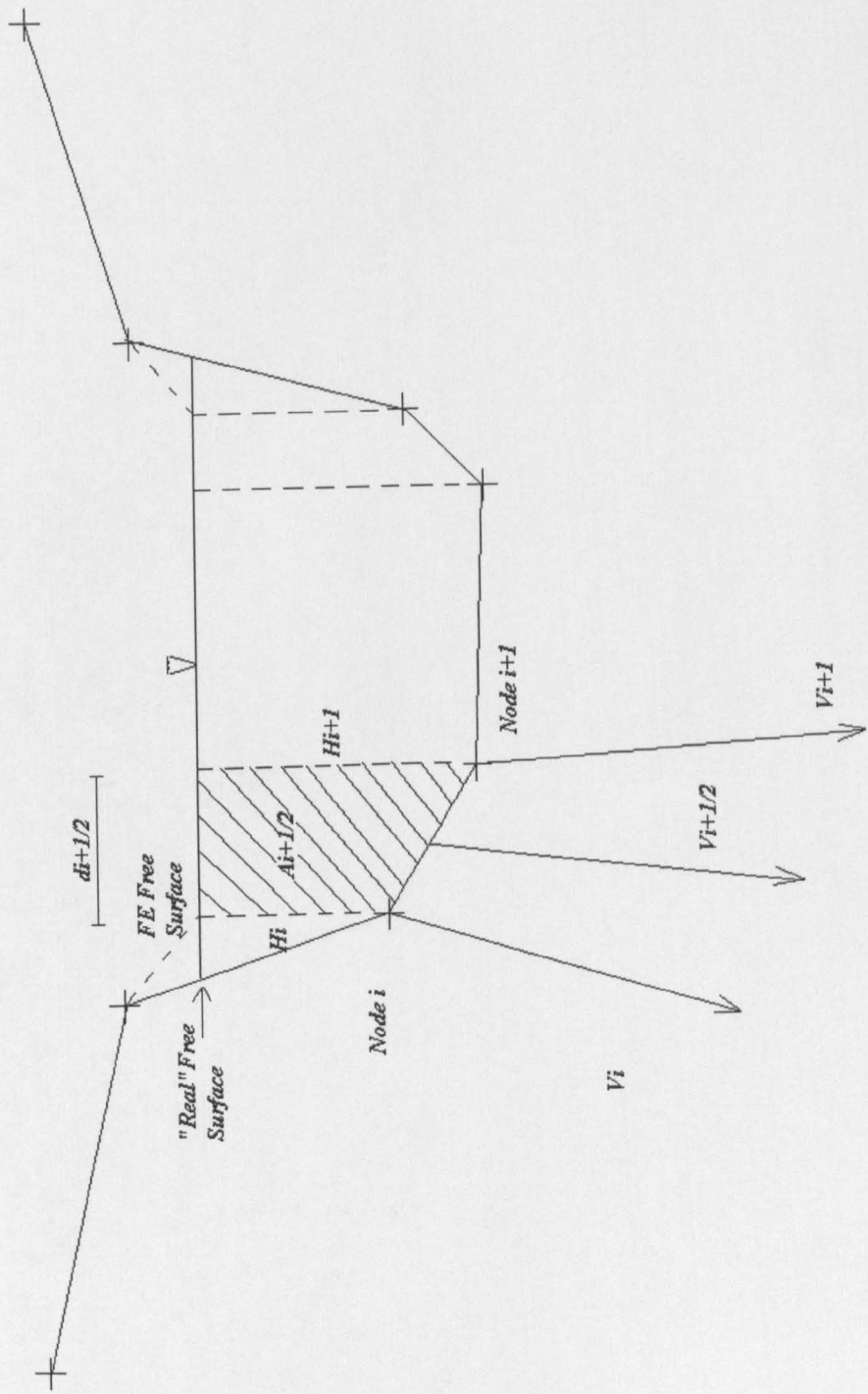


Fig. 4.21 – Schematic Representation of the Outlet Cross-Section used to Implement the Subroutine Q3DSORTIE in TELEMAR

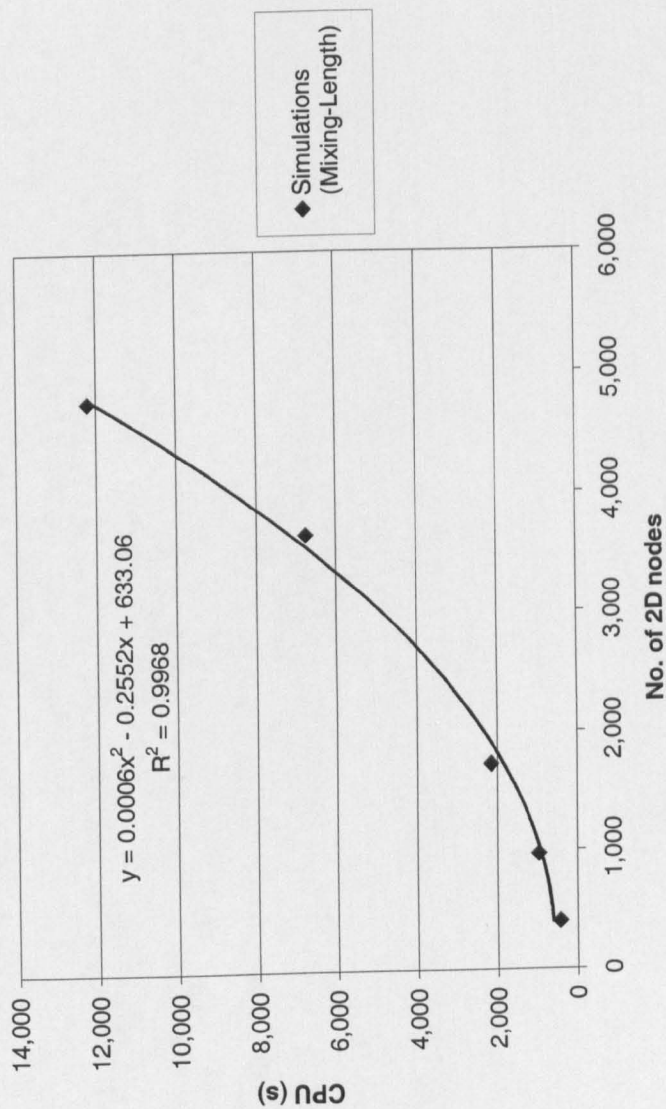


Fig. 4.22 – Scalability of TELEMAC-2D for Simulations of the Ribble Reach

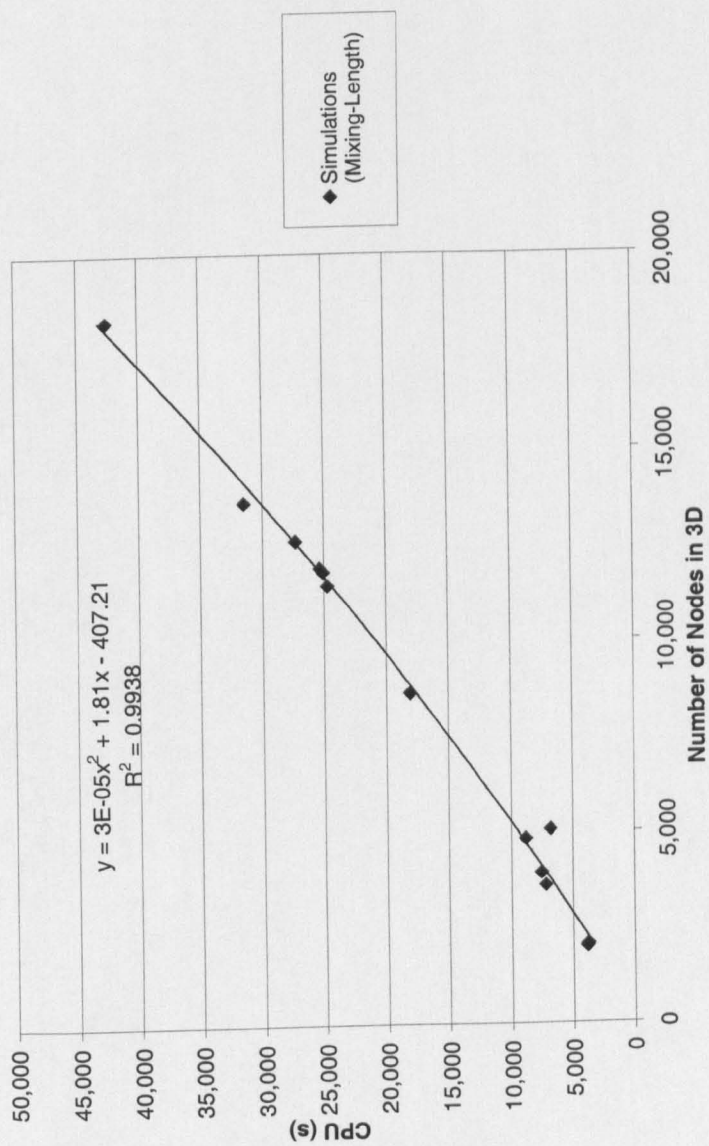


Fig. 4.23 – Scalability of TELEMAC-3D for Simulations of Ribble Reach

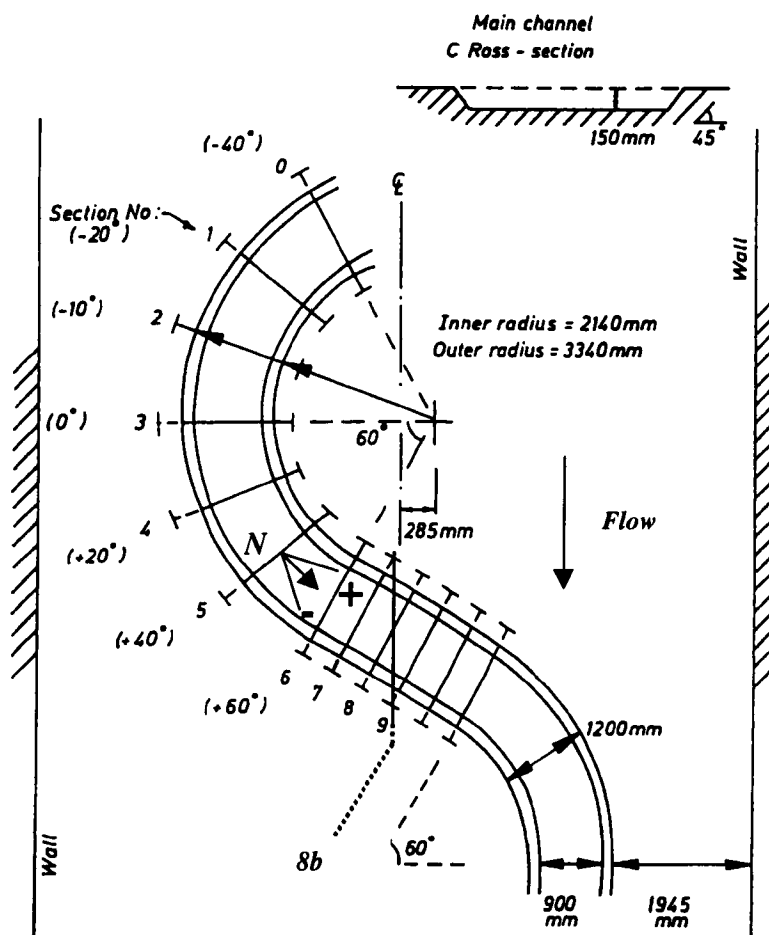
# **Chapter 5:**

## **Numerical Models Evaluation**

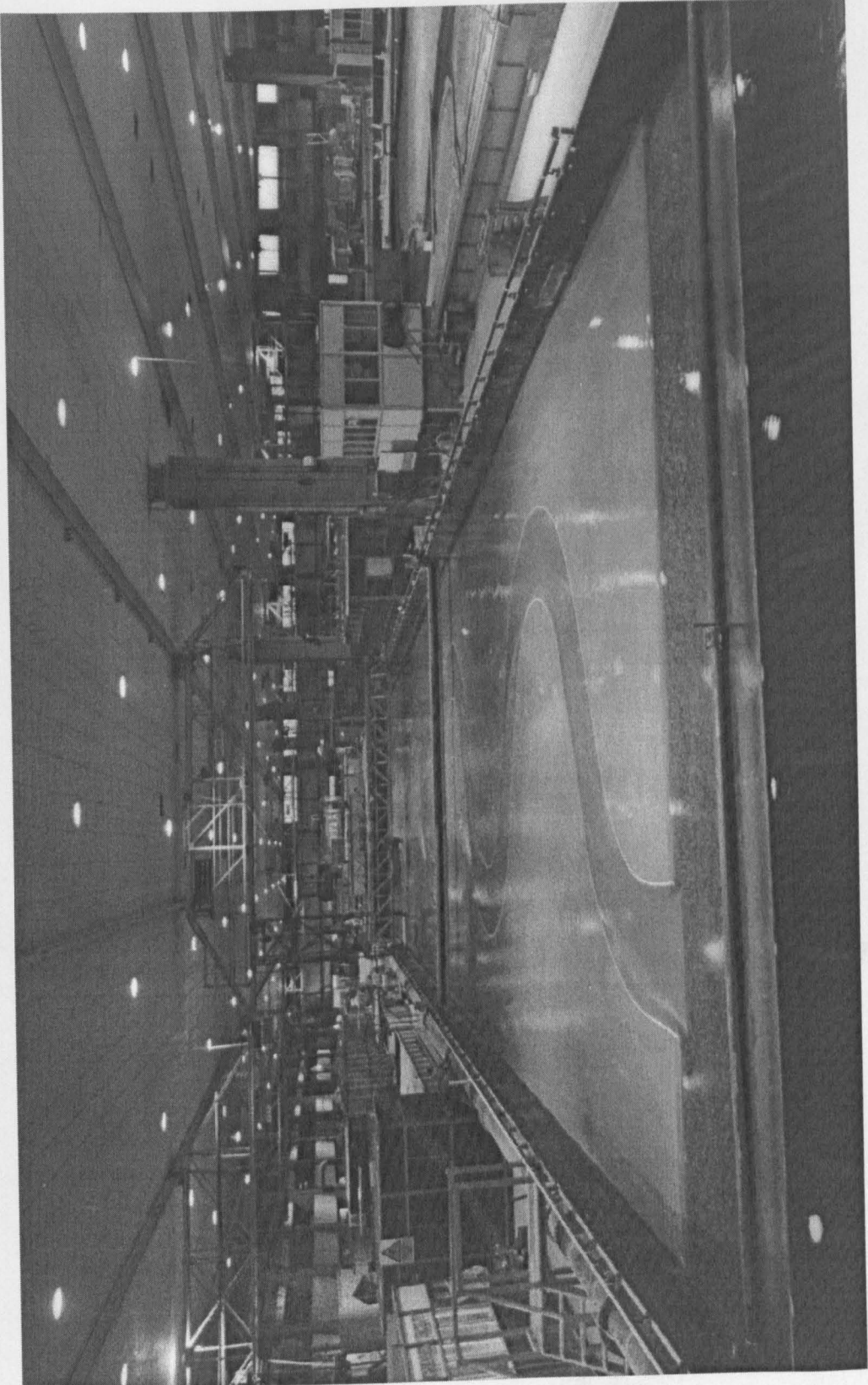
### **- The Flood Channel Facility Test Case**

**Figures for Chapter 5**

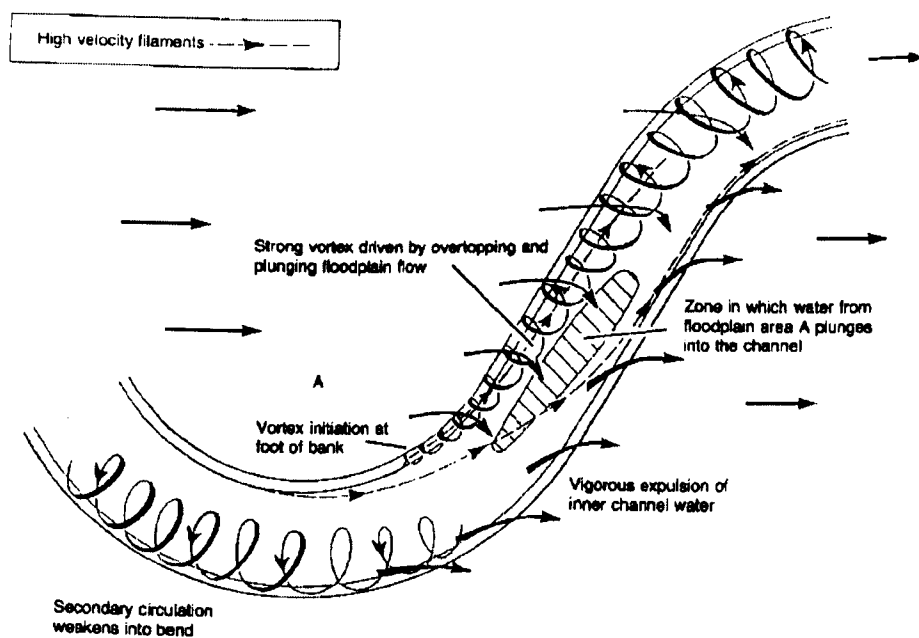




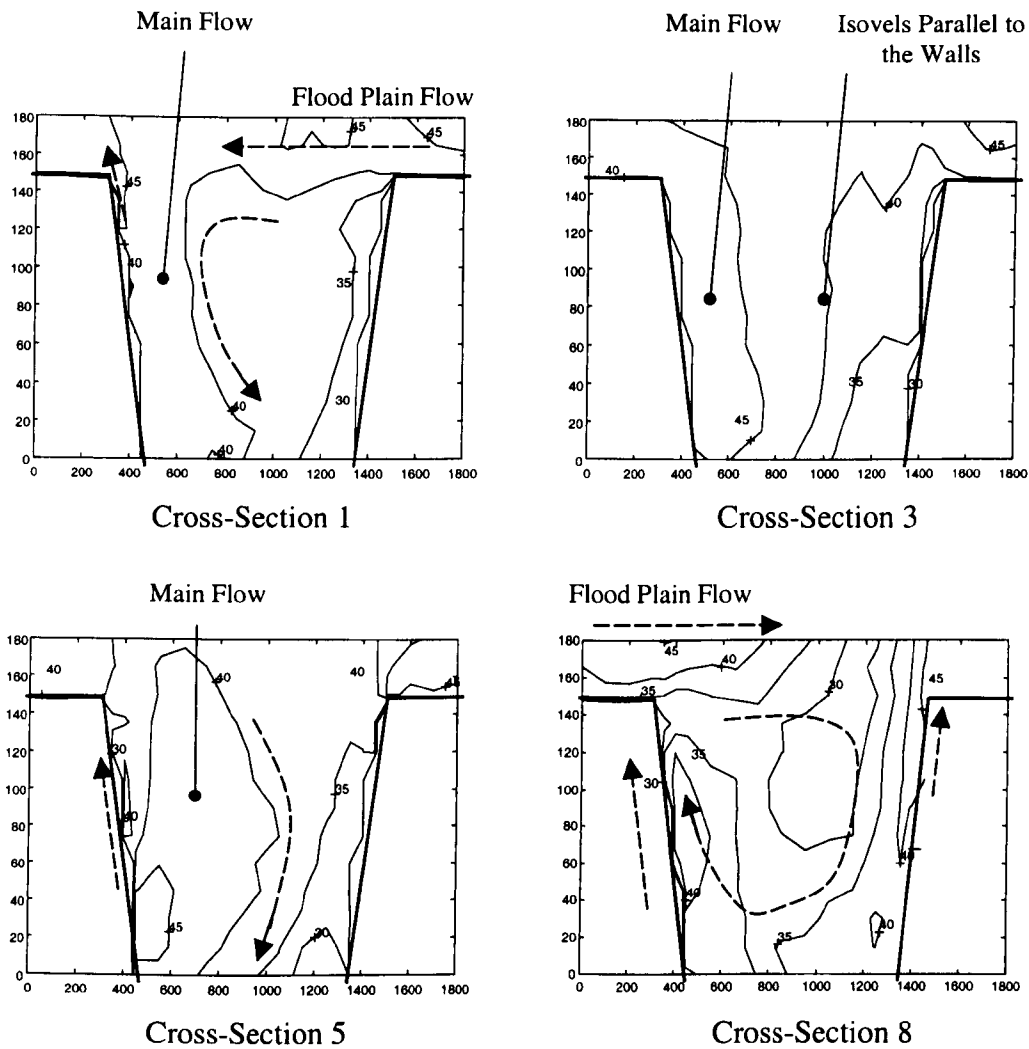
**Fig. 5.1. – Plan View Design of the 60 Degree Flood Channel Facility Programme Series B Flume (modified from Ervine et al., 1993)**



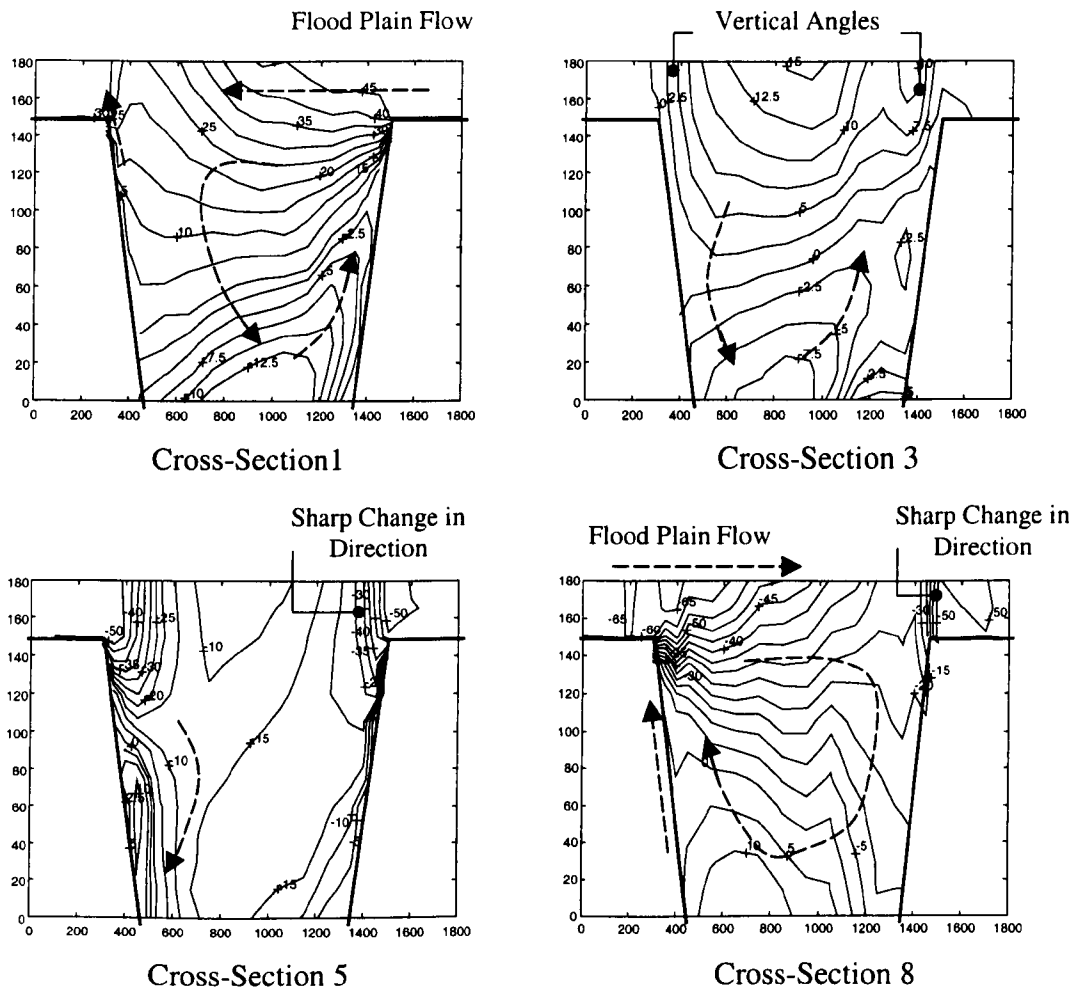
**Fig. 5.2 – Photograph of 60 Degree Flood Channel Facility Programme Series B Flume**



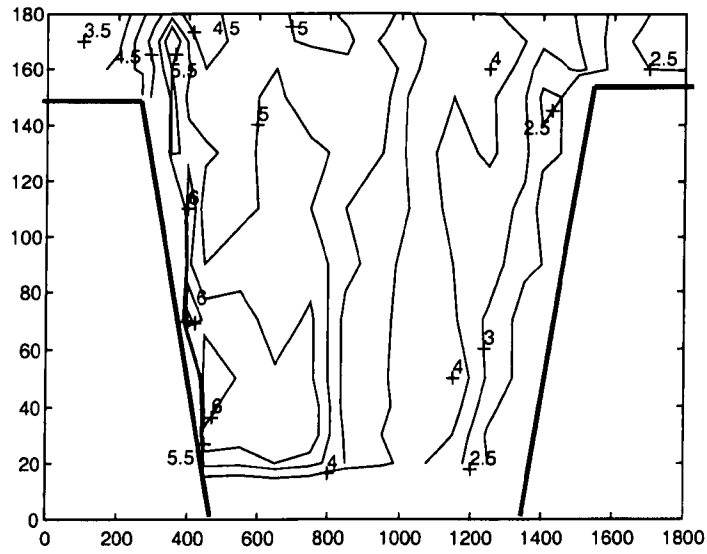
**Fig. 5.3 – Flow Structure at a Bend in a Meandering Compound Channel Flow  
(after Willetts and Hardwick, 1993)**



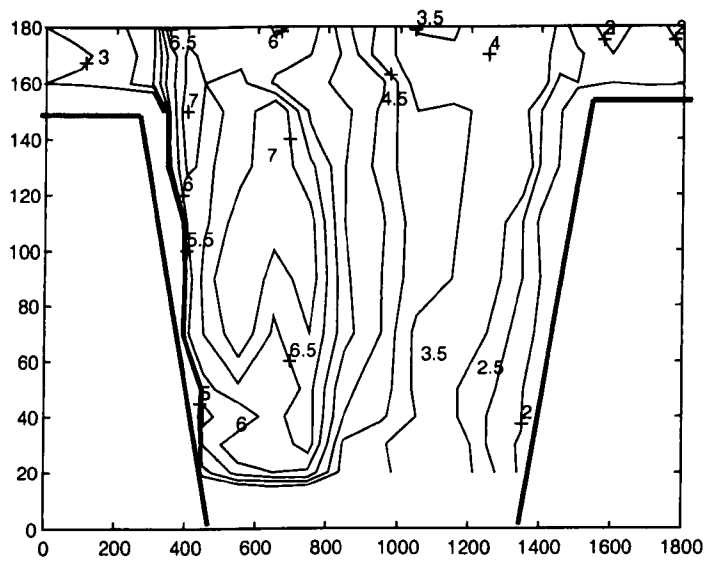
**Fig. 5.4 – FCF B23 Velocity Norm Data (cm/s) at Cross-Sections 1, 3, 5 and 8 (looking downstream)**



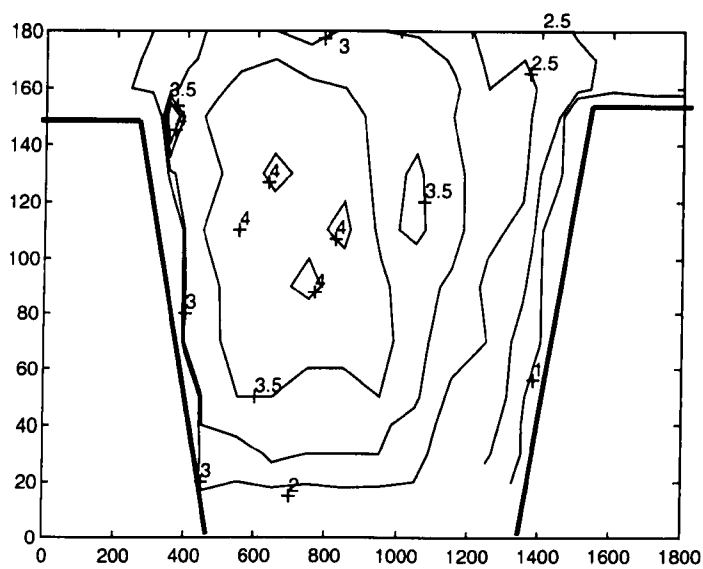
**Fig. 5.5 – FCF B23 Direction Angle Data (deg.) at Cross-Sections 1, 3, 5 and 8 (looking downstream)**



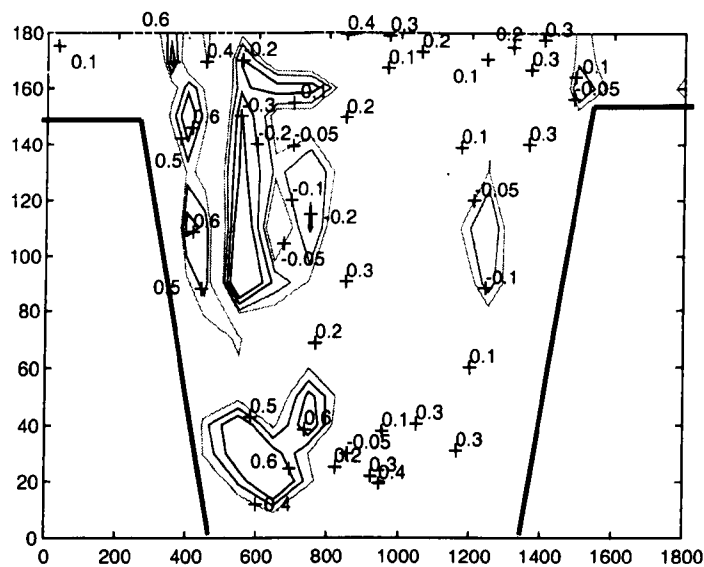
**Fig. 5.6 – FCF B23 Turbulence Data at Cross-Section 3:  $u'$  (cm/s)**



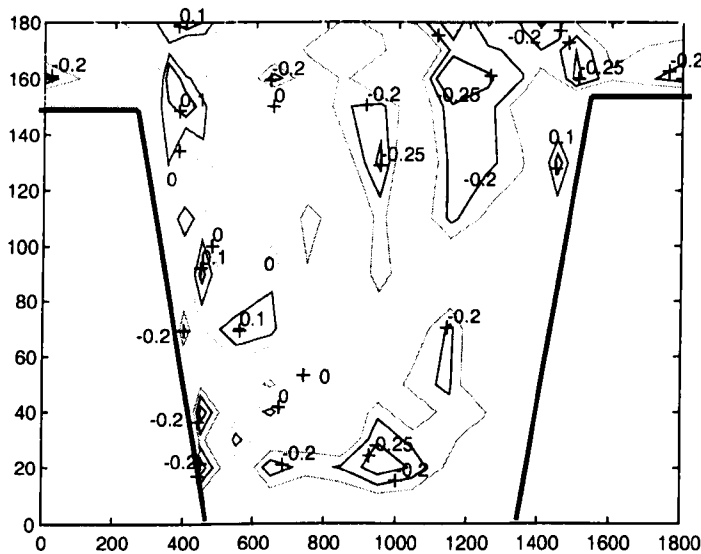
**Fig. 5.7 – FCF B23 Turbulence Data at Cross-Section 3:  $v'$  (cm/s)**



**Fig. 5.8 – FCF B23 Turbulence Data at Cross-Section 3:  $w'$  (cm/s)**

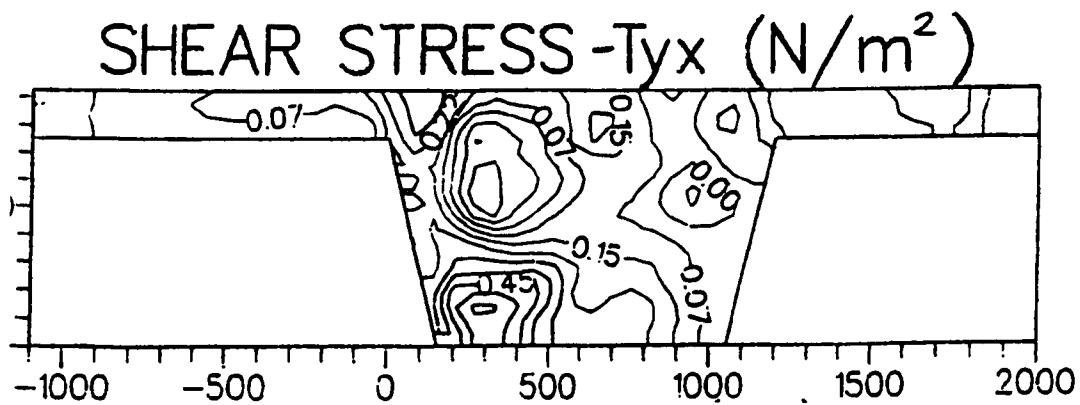


**Fig. 5.9 – FCF B23 Turbulence Data at Cross-Section 3:  $T_{yx}(N/m^2)$**

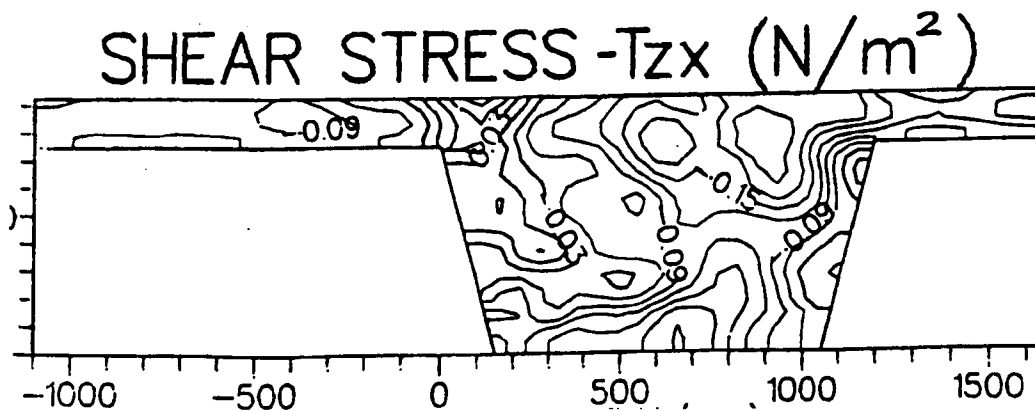


**Fig. 5.10 – FCF B23 Turbulence Data at Cross-Section 3:  $T_{zx}(N/m^2)$**

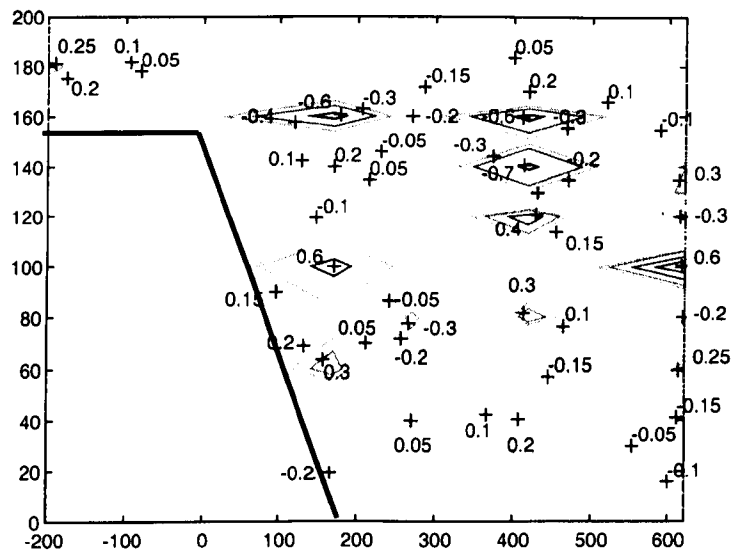




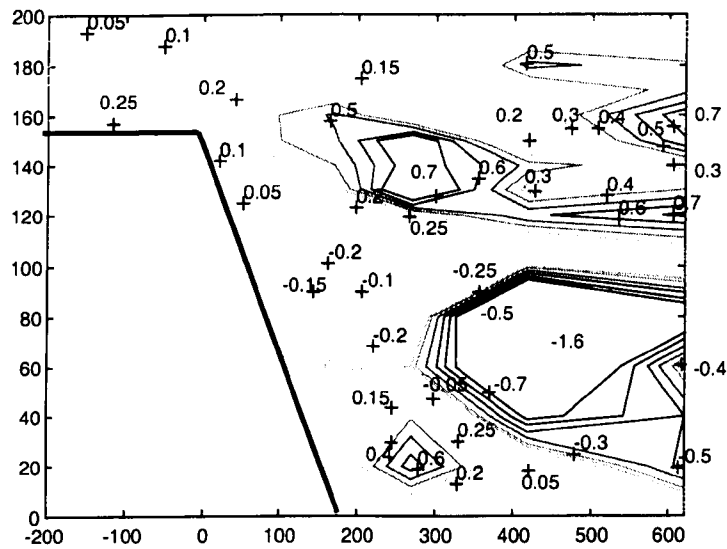
**Fig. 5.11 – Interpretation of FCF B23 Turbulence Data at the Cross-Over:  $T_{yx}(\text{N/m}^2)$**



**Fig. 5.12 – Interpretation of FCF B23 Turbulence Data at Cross-Section 3:  
 $T_{zx}(\text{N/m}^2)$**



**Fig. 5.13 – FCF B23 Turbulence Data at the Cross-Over:  $T_{yx}$ (N/m<sup>2</sup>)**



**Fig. 5.14 – FCF B23 Turbulence Data at Cross-Section 3:  $T_{zx}$ (N/m<sup>2</sup>)**

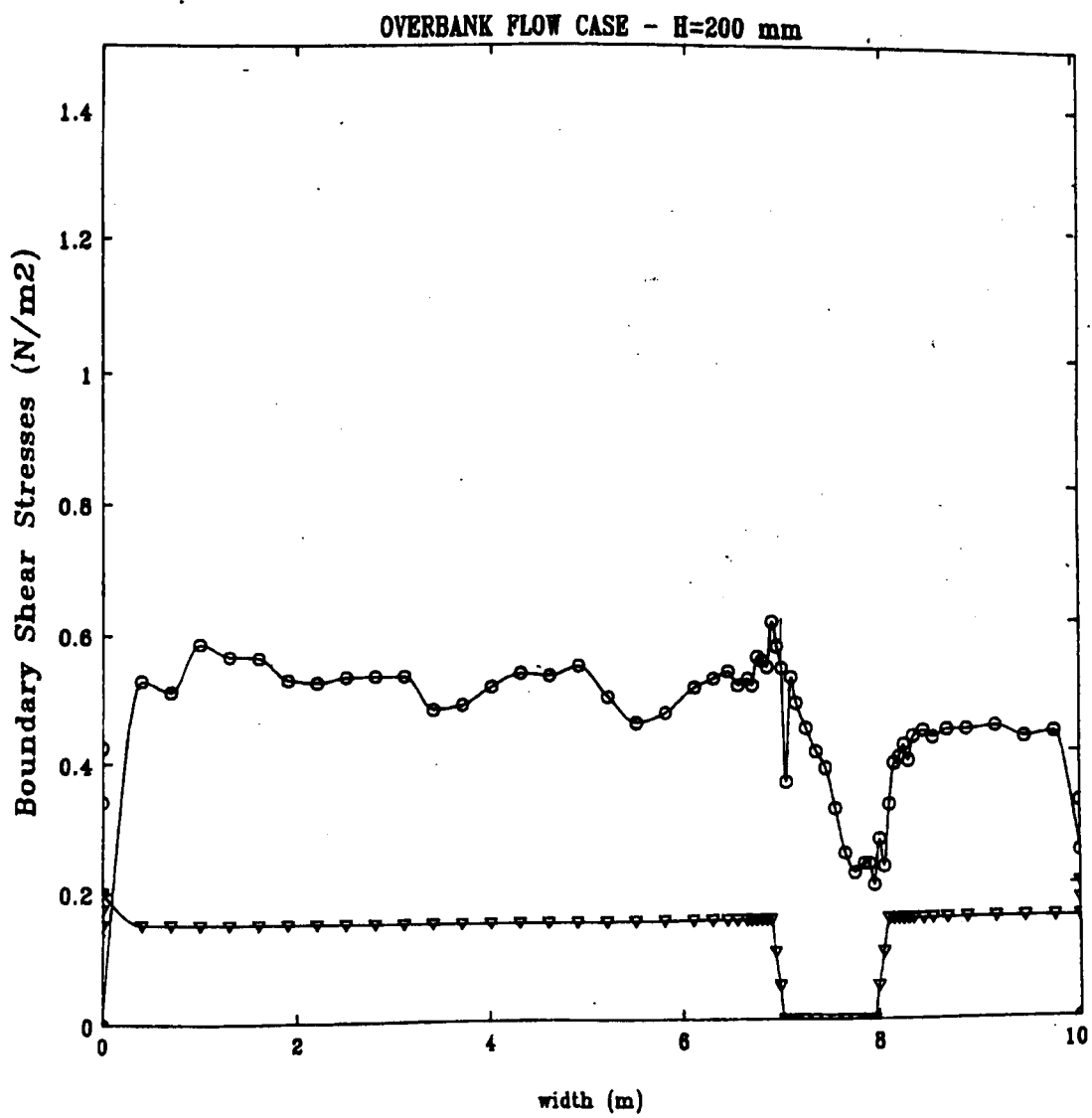


Fig. 5.15 - FCF B23 Bed Shear Stress Data at Cross-Section 3 ( $\text{N/m}^2$ )

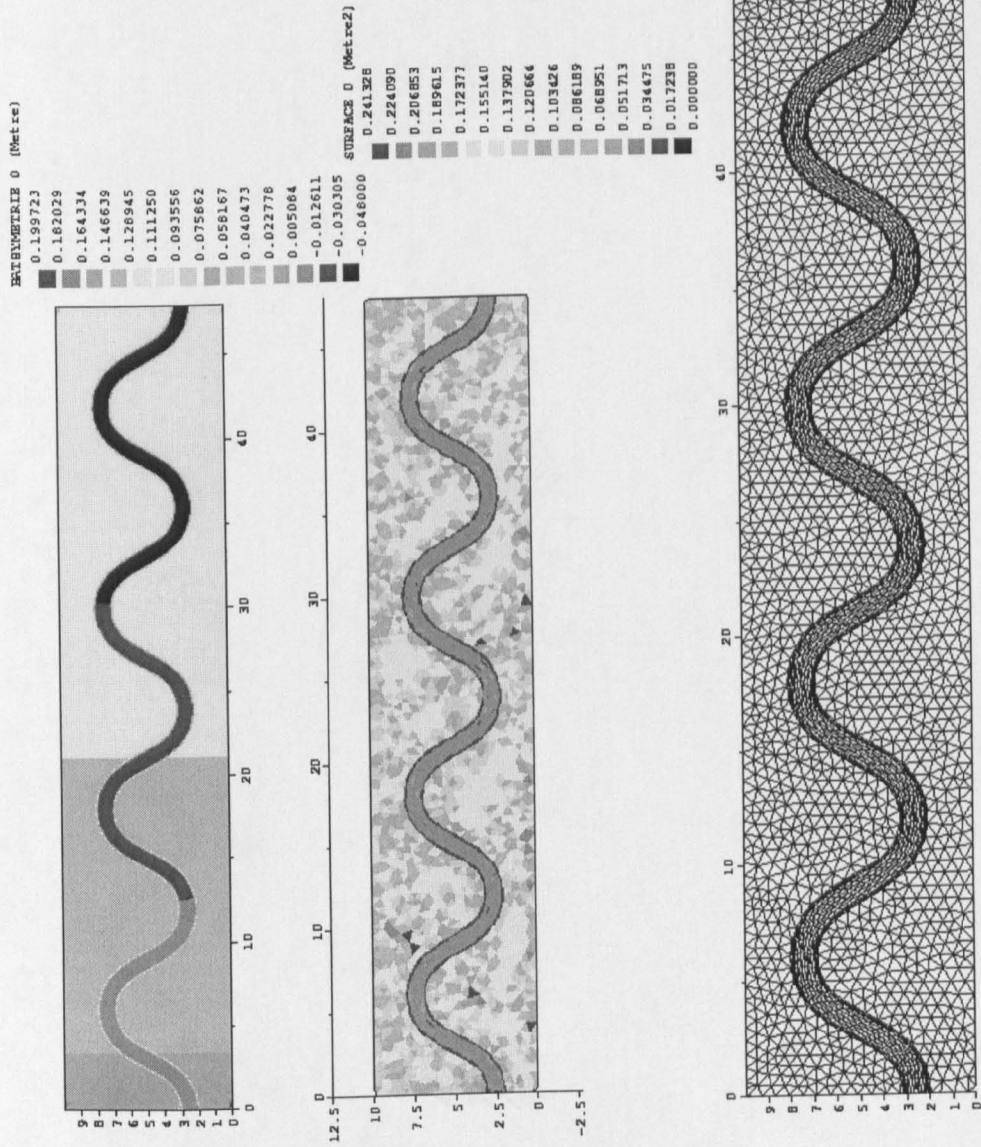


Fig. 5.16 – FCF Series B Geometry and Mesh Characteristics for TELEMAR

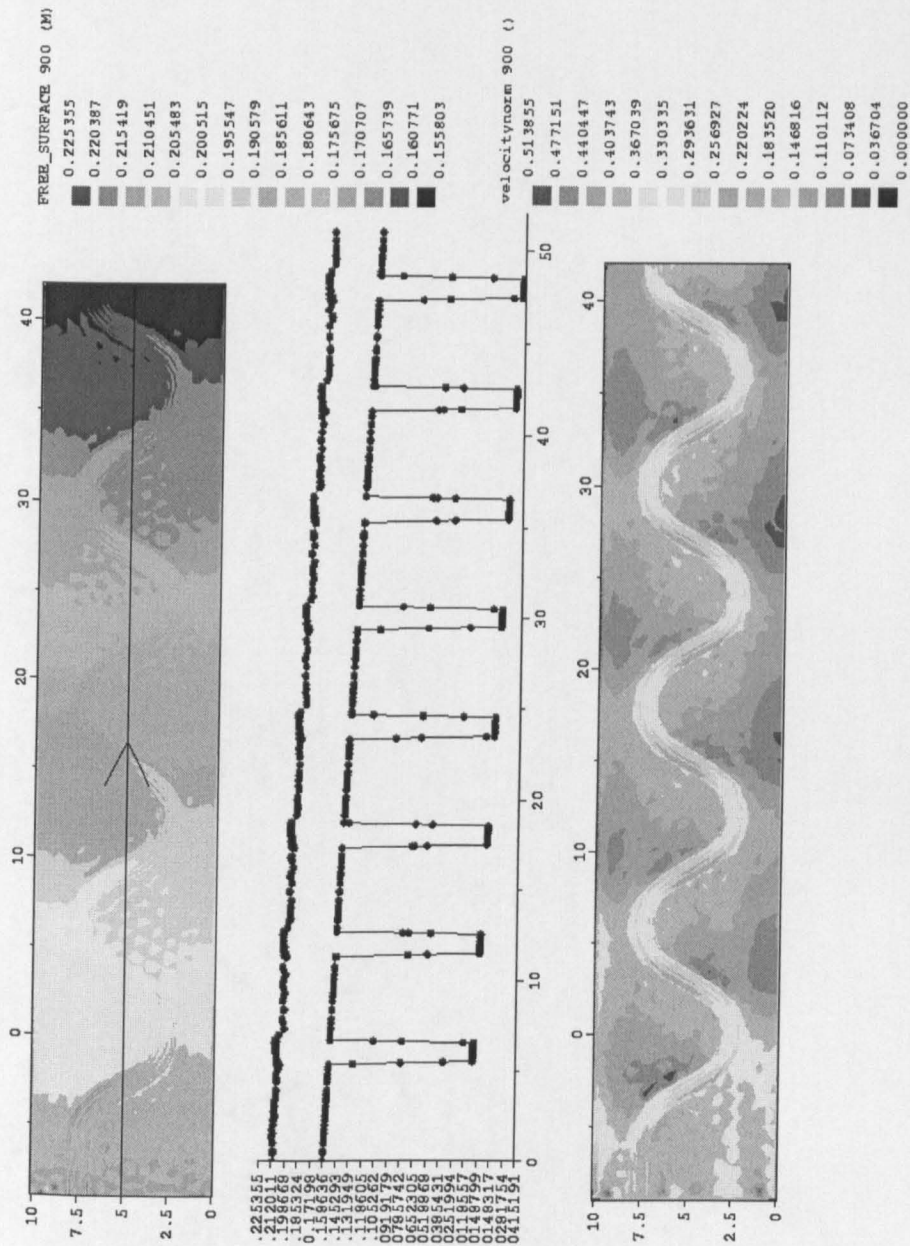


Fig. 5.17 – FCF B23 TELEMAC Free-Surface Profile and Dept-Averaged Velocity ( $C = 68 \text{ m}^{1/2}/\text{s}$ , Mixing-Length Model)

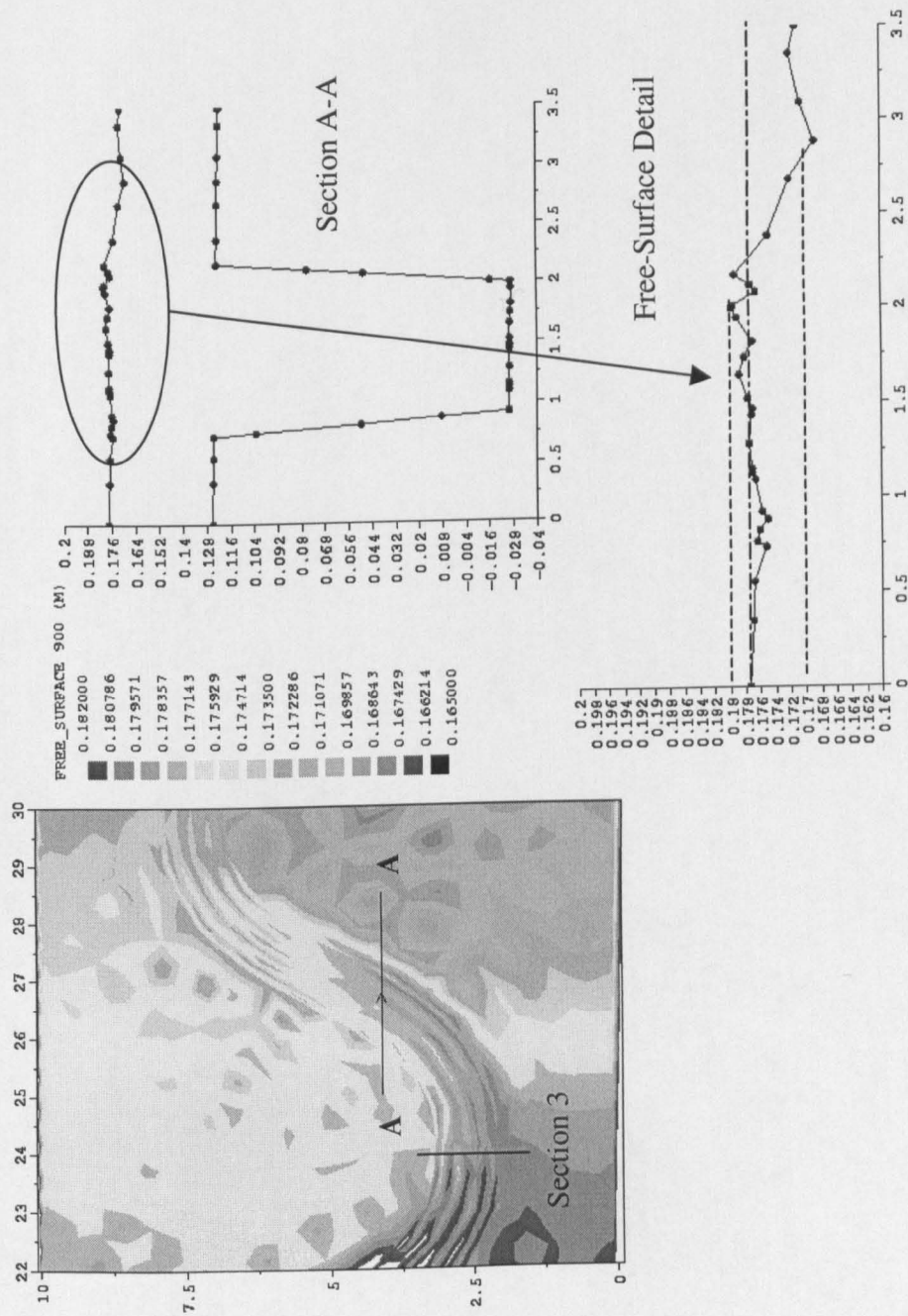
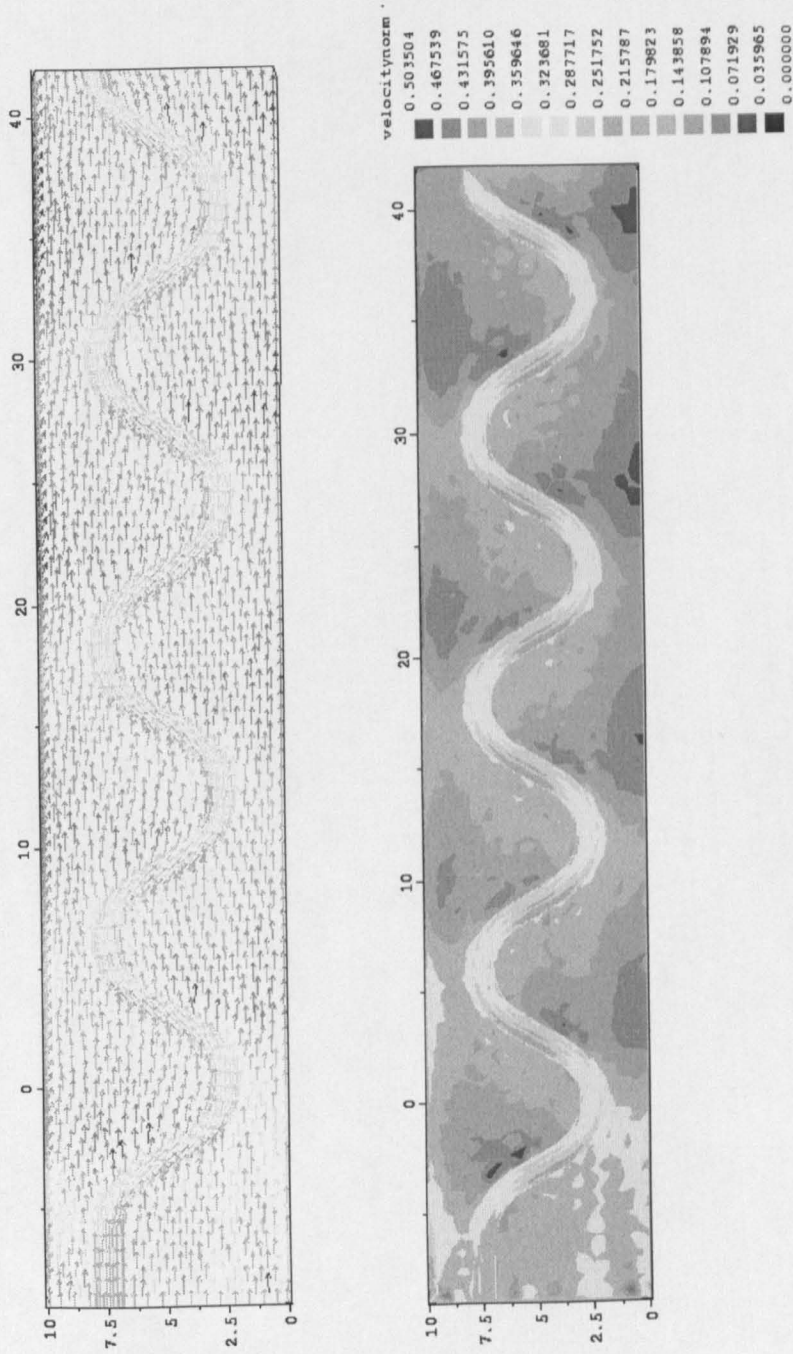


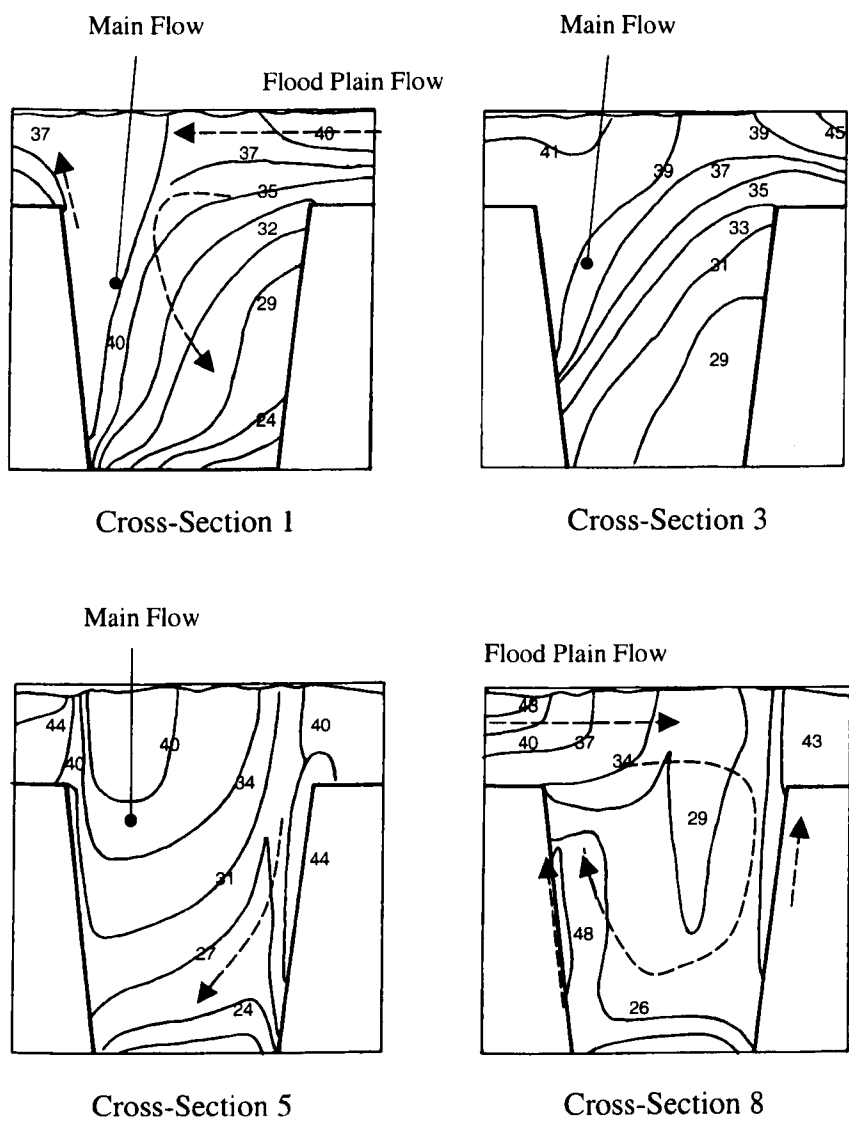
Fig. 5.18 – FCF B23 TELEMAC Free-Surface Contraction and Expansion past the Bend ( $C = 68 \text{ m}^{1/2}/\text{s}$ , Mixing-Length Model)



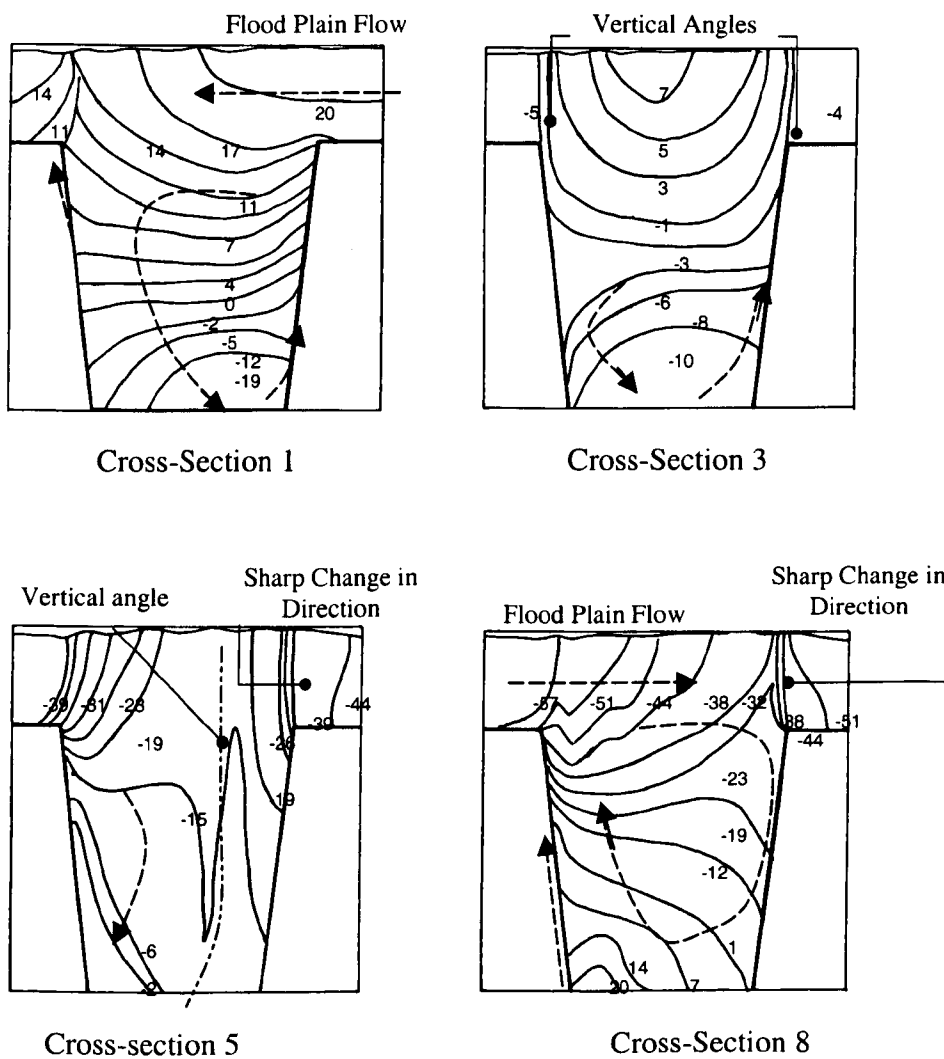


**Fig. 5.19 – FCF B23 TELEMAC Depth Averaged Velocity Field ( $C = 68 \text{ m}^{1/2}/\text{s}$ , Mixing Length Model)**

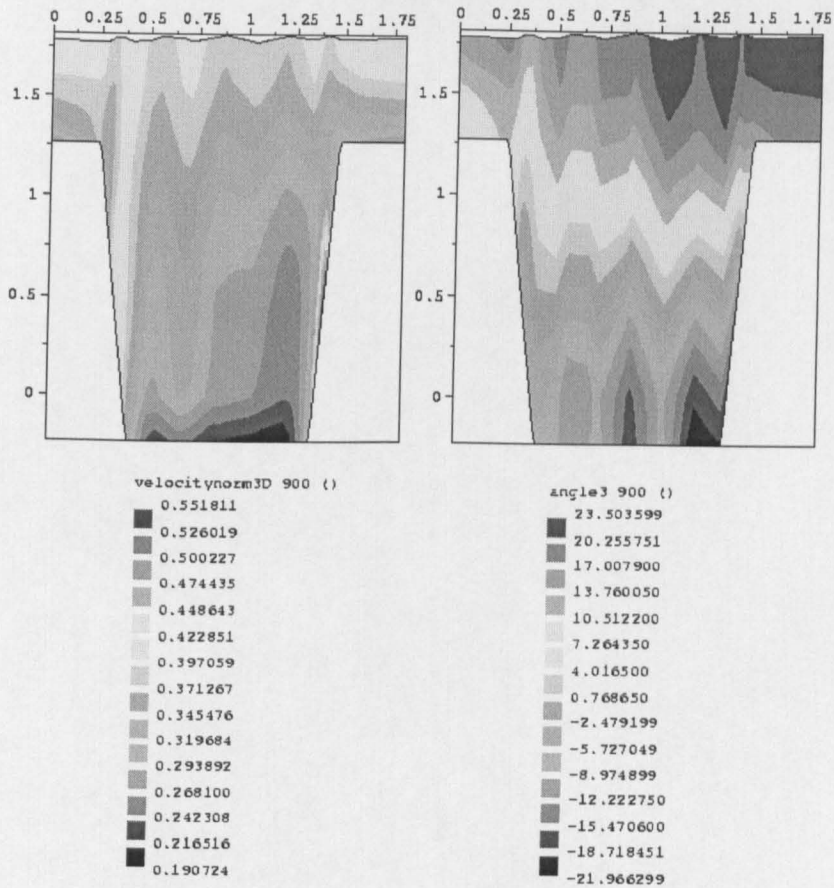




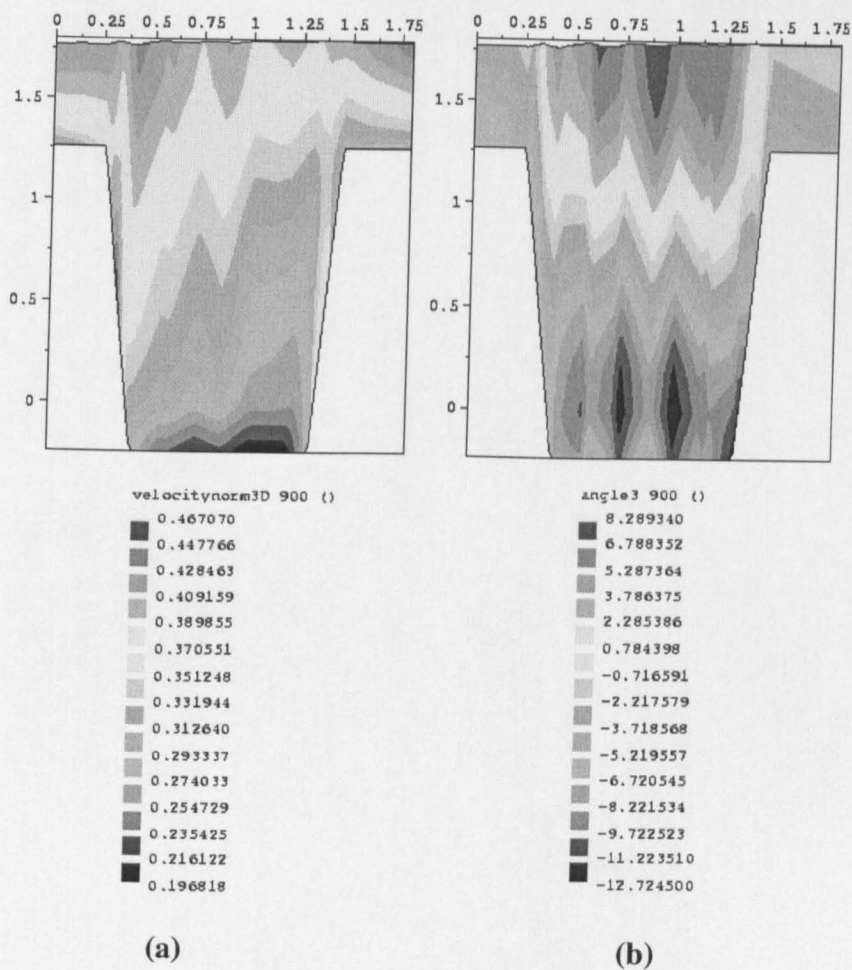
**Fig. 5.20 – FCF B23 TELEMAC Velocity Norm Predictions (cm/s) at Cross-Sections 1, 3, 5 and 8 ( $C = 68 \text{ m}^{1/2}/\text{s}$ , Mesh TELEMAC FCF-1, Mixing-Length Model)**



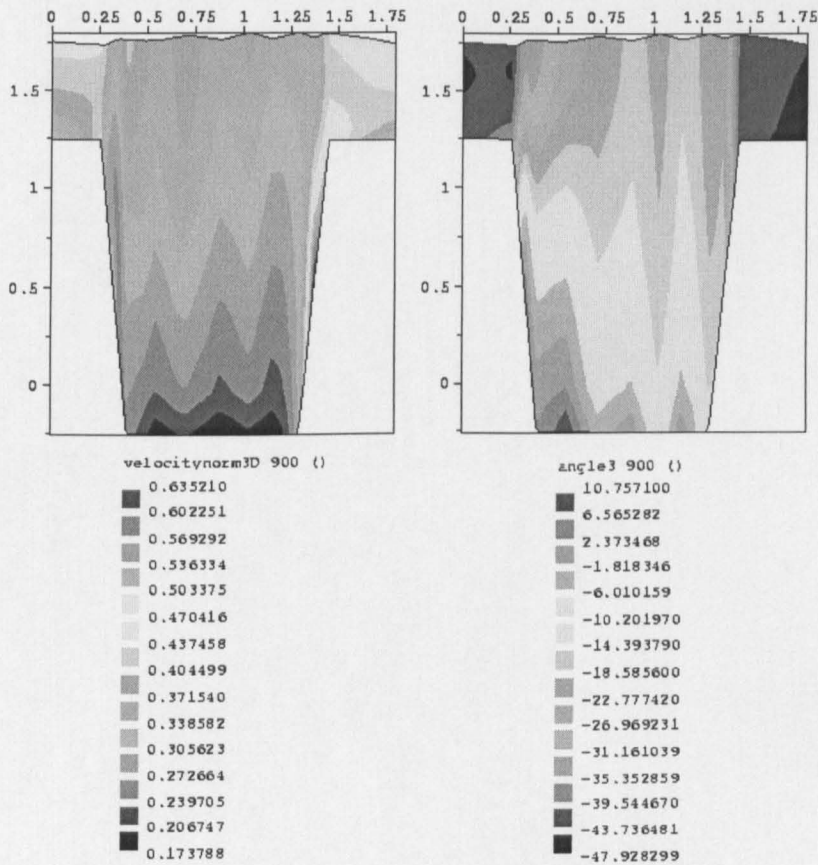
**Fig. 5.21 – FCF B23 TELEMAC Velocity Angle Predictions (deg.) at Cross-Sections 1, 3, 5 and 8**  
**( $C = 68 \text{ m}^{1/2}/\text{s}$ , Mesh TELEMAC FCF-1, Mixing-Length Model)**



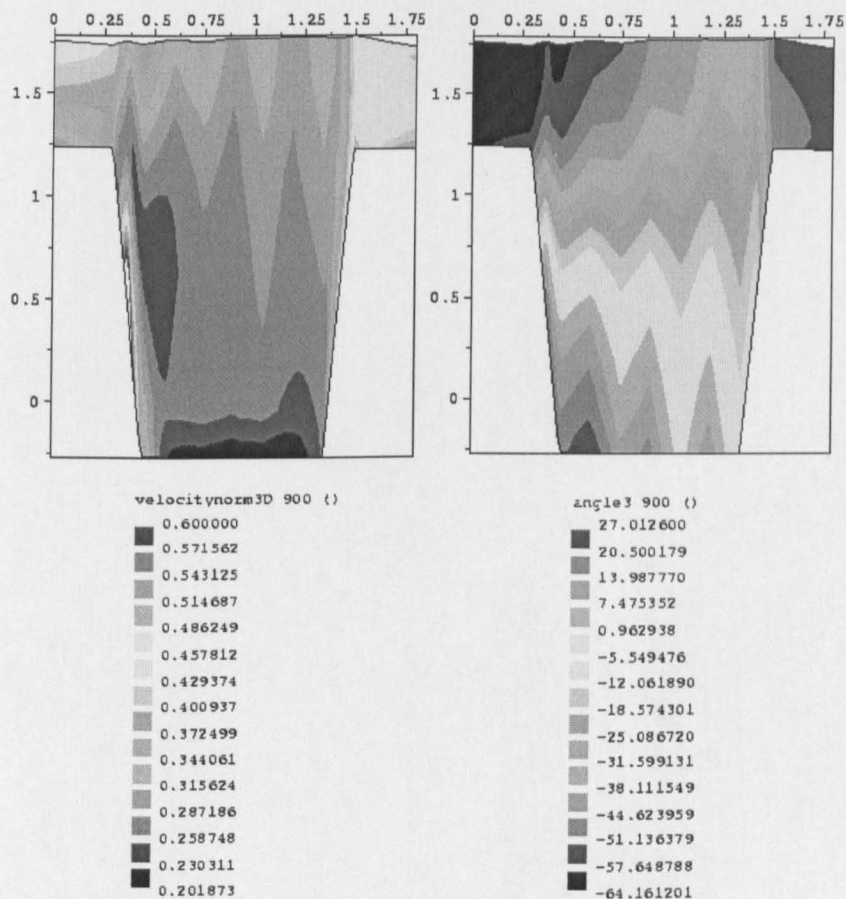
**Fig. 5.22 – FCF B23 TELEMAC Outputs for Cross-Section 1:**  
**(a) Velocity Norm (left; m/s)**  
**(b) Angle (deg.)**  
**( $C = 68 \text{ m}^{1/2}/\text{s}$ , Mesh TELEMAC FCF-1, Mixing-Length Model)**



**Fig. 5.23 – FCF B23 TELEMAC Outputs for Cross-Section 3:**  
**(a) Velocity Norm (left; m/s)**  
**(b) Angle (deg.)**  
**( $C = 68 \text{ m}^{1/2}/\text{s}$ , Mesh TELEMAC FCF-1, Mixing-Length Model)**



**Fig. 5.24 – FCF B23 TELEMAC Outputs for Cross-Section 5:**  
**(a) Velocity Norm (left; m/s)**  
**(b) Angle (deg.)**  
**( $C = 68 \text{ m}^{1/2}/\text{s}$ , Mesh TELEMAC FCF-1, Mixing-Length Model)**



**Fig. 5.25 – FCF B23 TELEMAC Outputs for Cross-Section 8:**  
**(a) Velocity Norm (left; m/s)**  
**(b) Angle (deg.)**  
**( $C = 68 \text{ m}^{1/2}/\text{s}$ , Mesh TELEMAC FCF-1, Mixing-Length Model)**

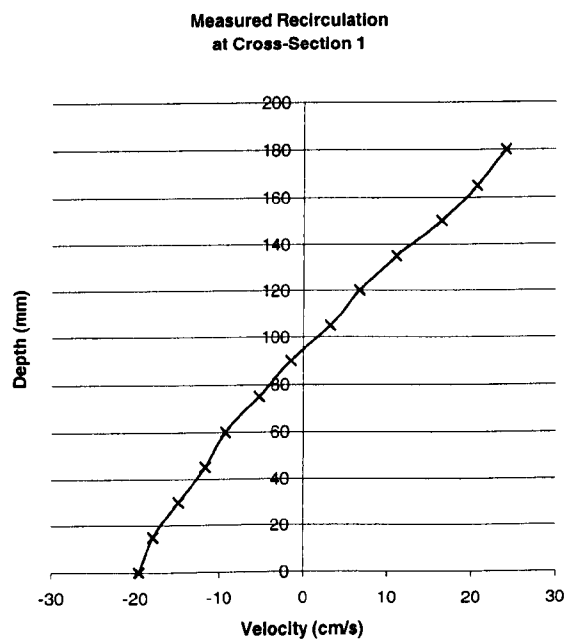
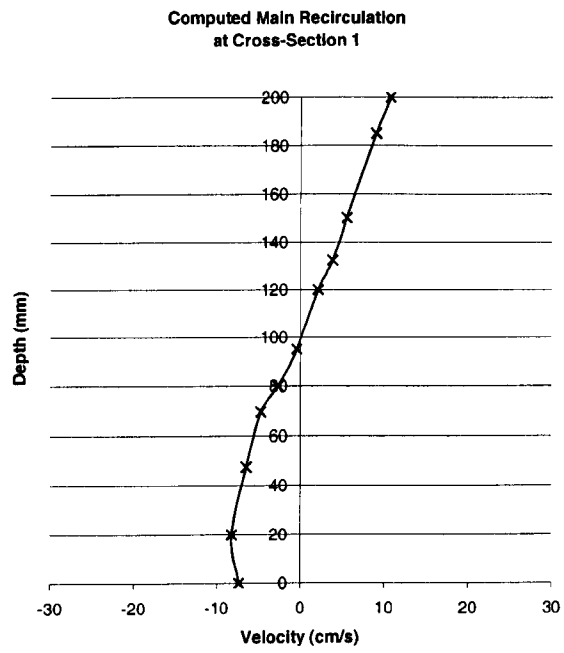
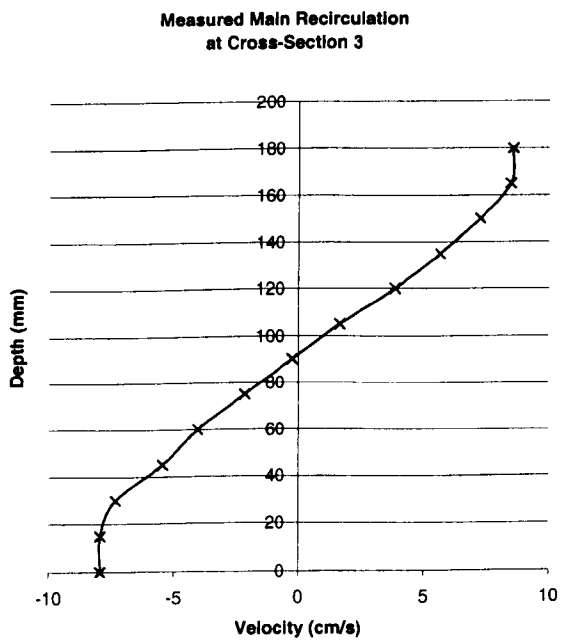
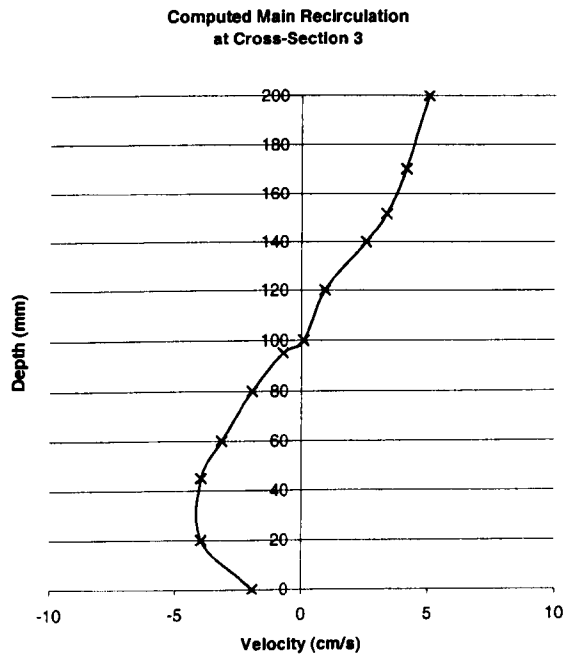
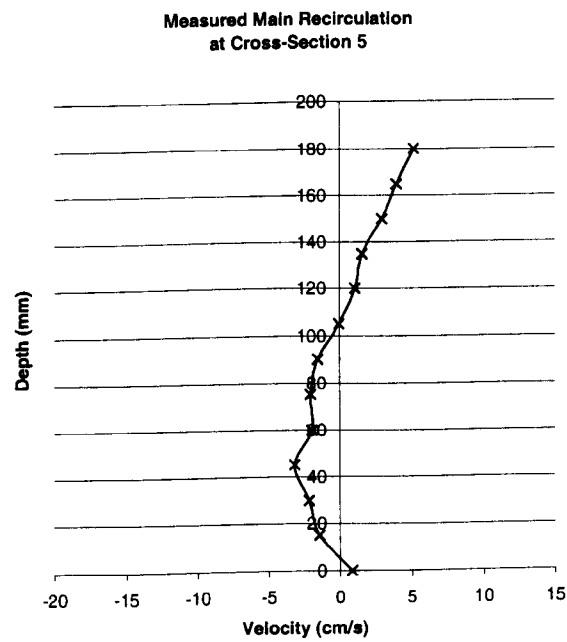
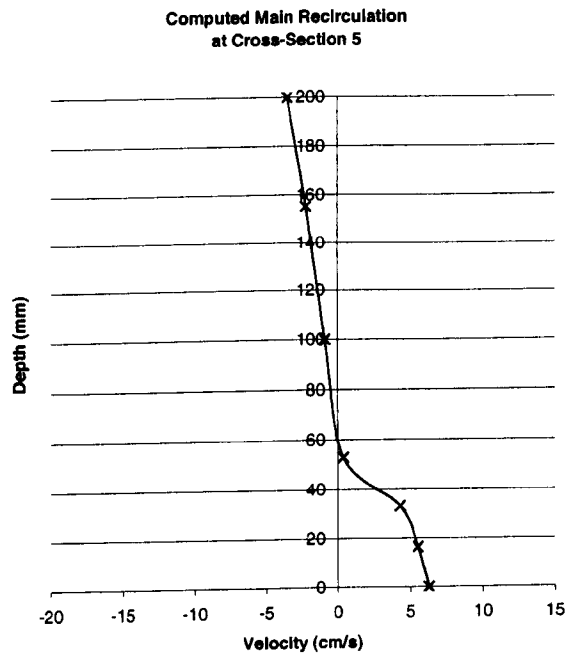


Fig. 5.26 – FCF B23 TELEMAC Model: Recirculation at Cross-Section 1

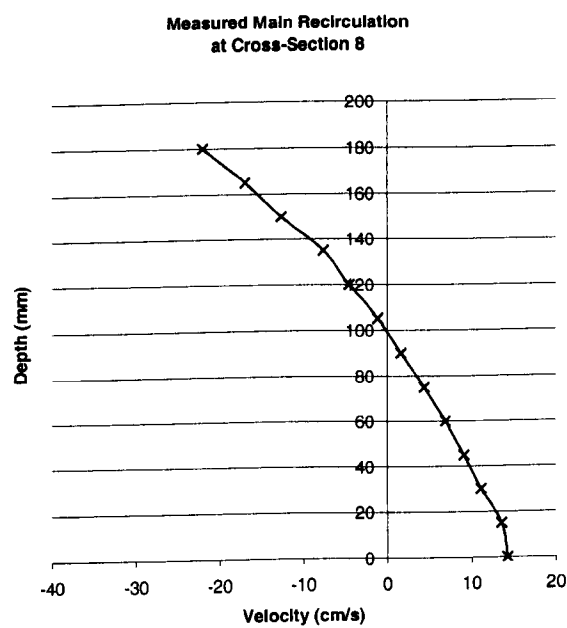
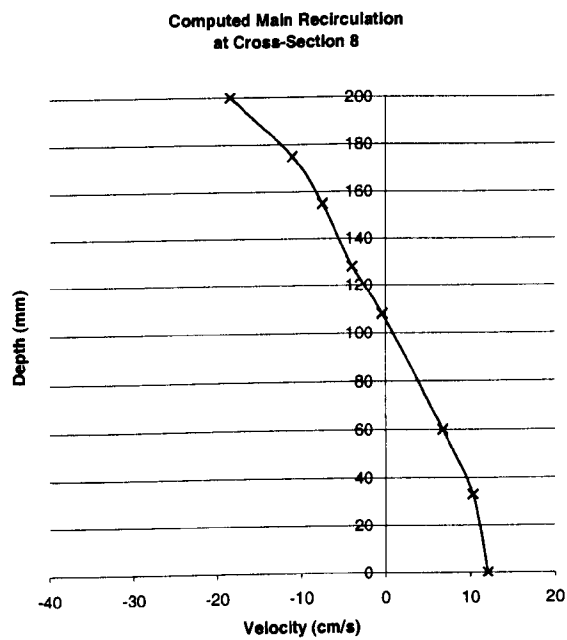




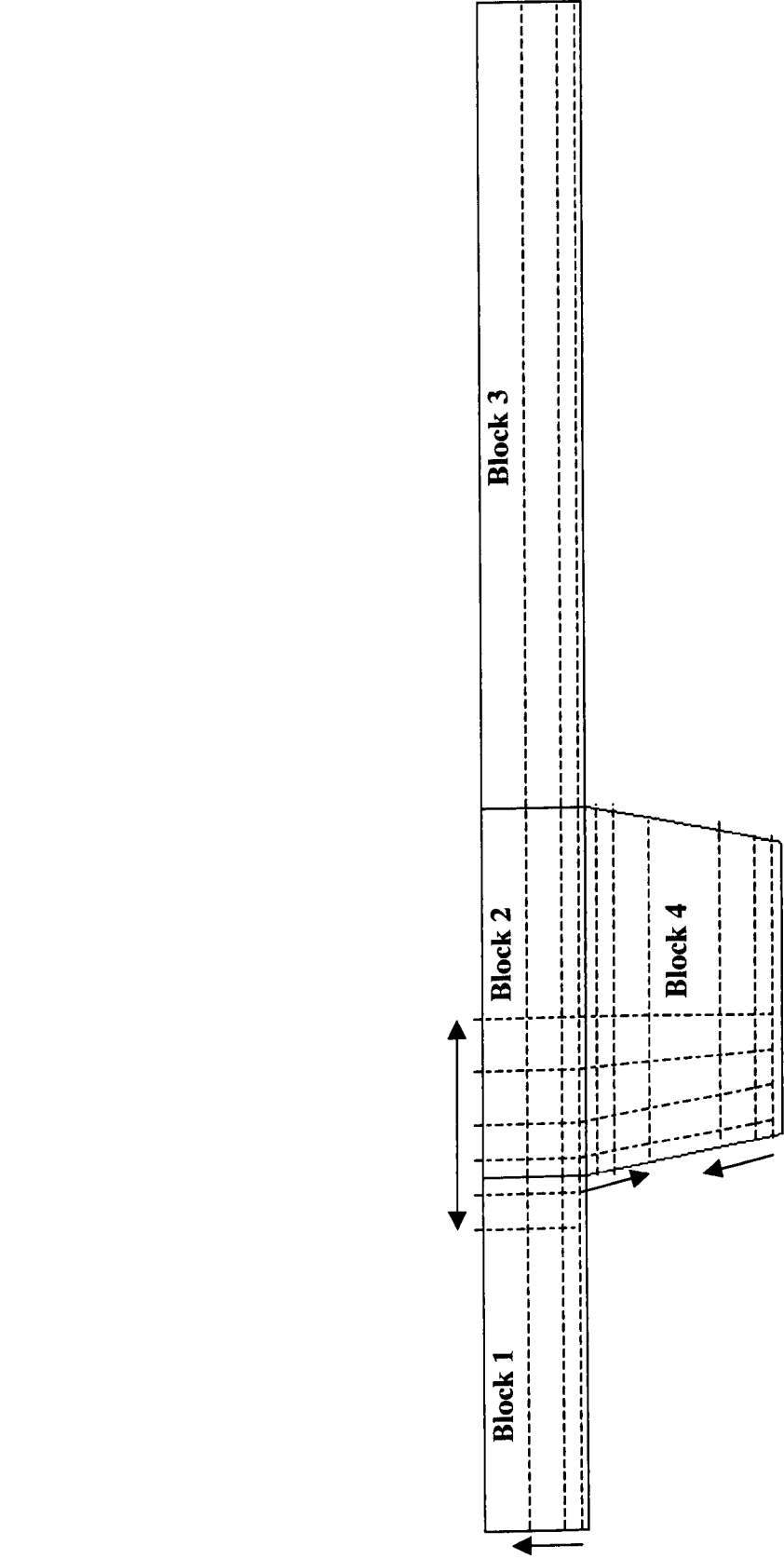
**Fig. 5.27 – FCF B23 TELEMAC Model: Recirculation at Cross-Section 3**



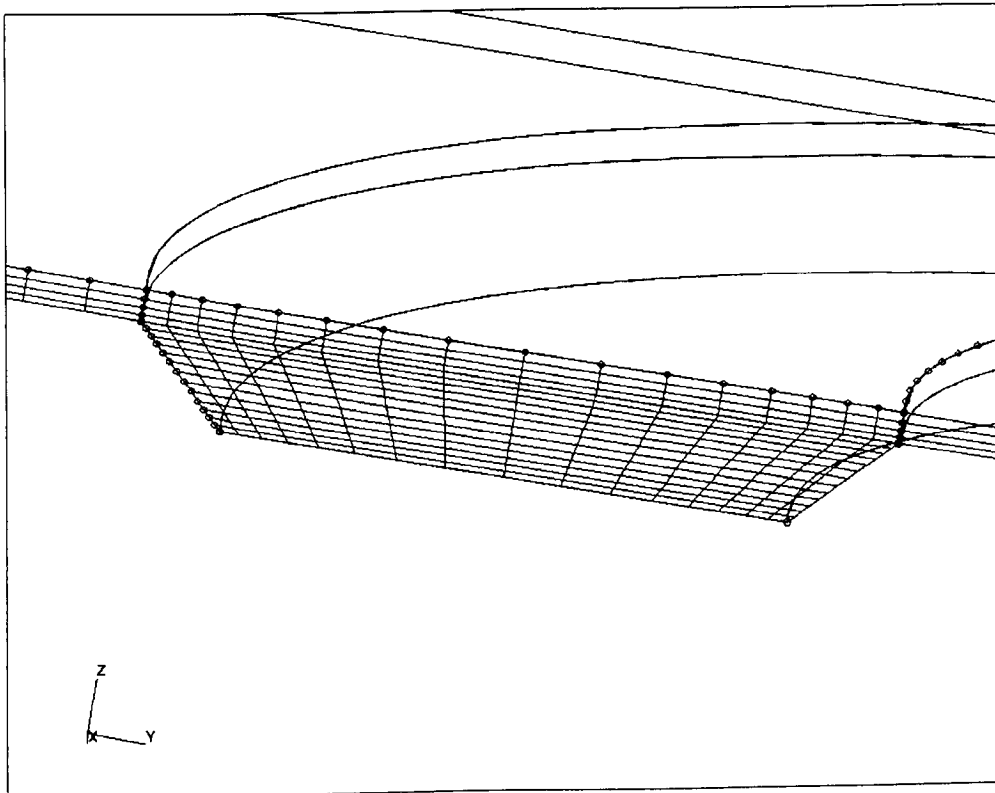
**Fig. 5.28 – FCF B23 TELEMAC Model: Recirculation at Cross-Section 5**



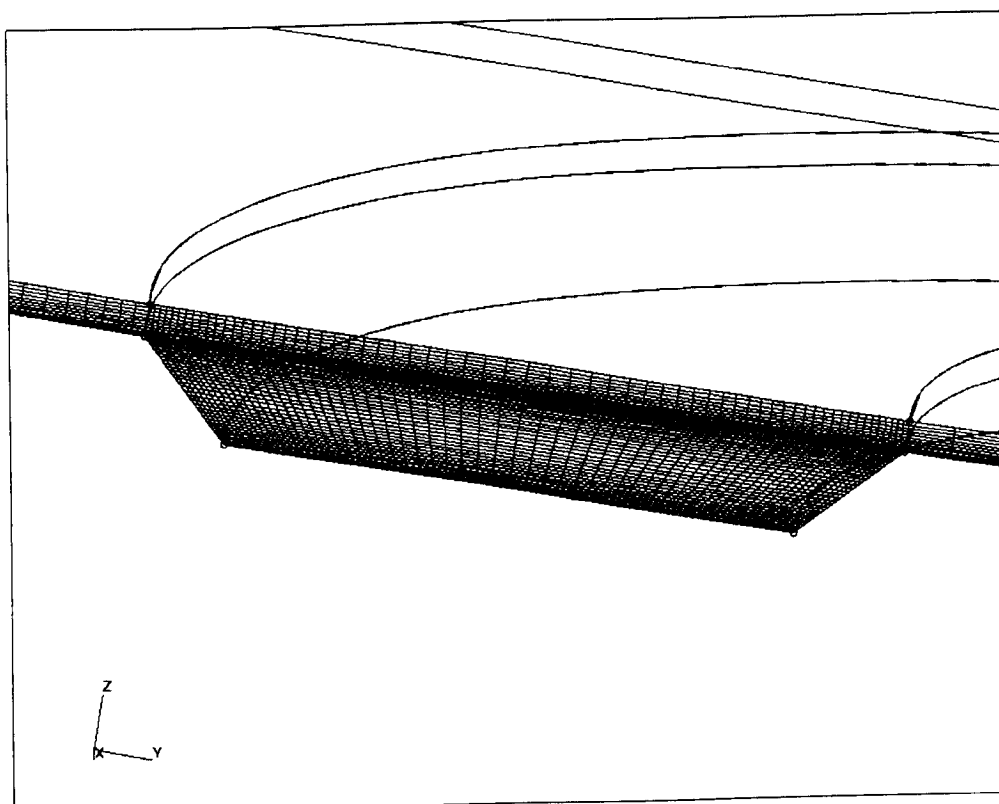
**Fig. 5.29 – FCF B23 TELEMAC Model: Recirculation at Cross-Section 8**



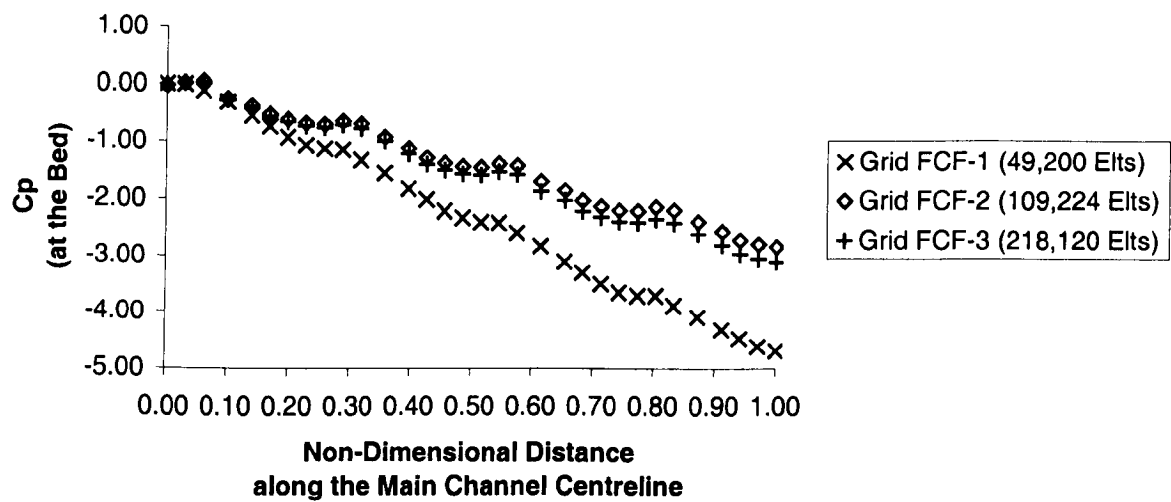
**Fig. 5.30 – Construction of the CFX Numerical Grid of the FCF**



**Fig. 5.31 – CFX Grid FCF-1**

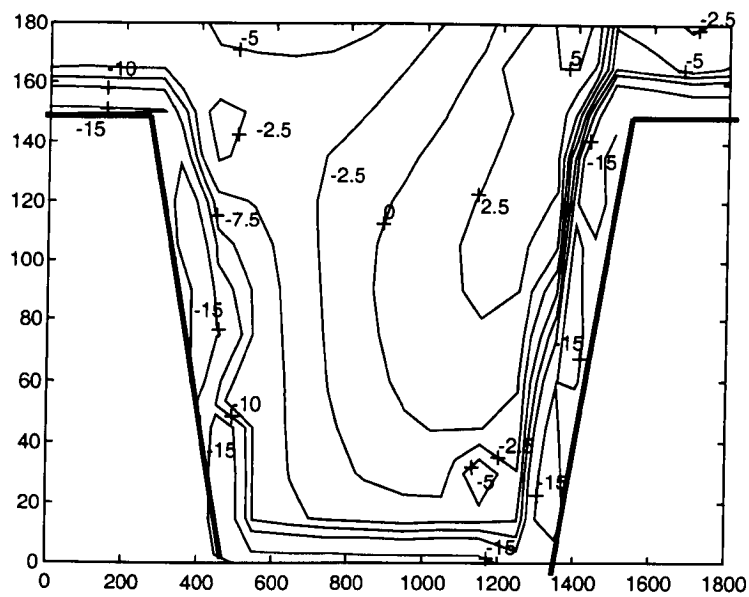


**Fig. 5.32 – CFX Grid FCF-3**

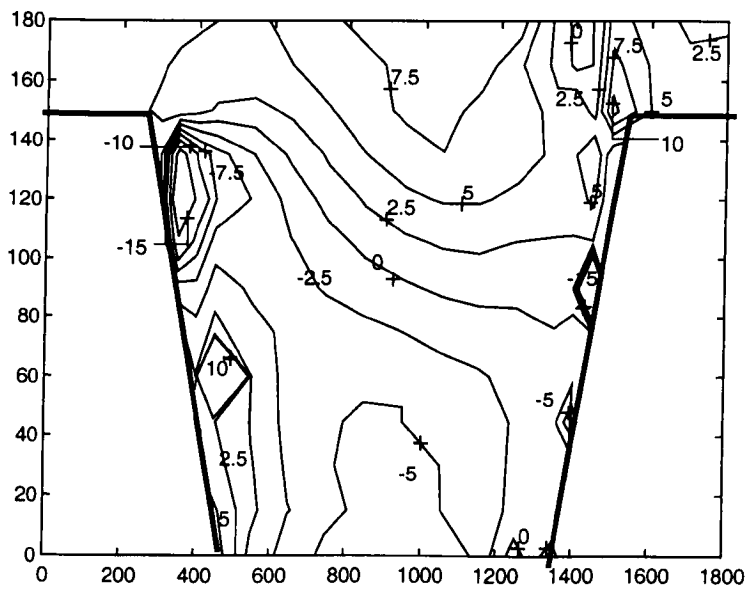


**Fig. 5.33 – Mesh Independence: Comparison of the Non-dimensionalized Pressure Term  $C_p$  for Different Mesh Resolution in CFX**

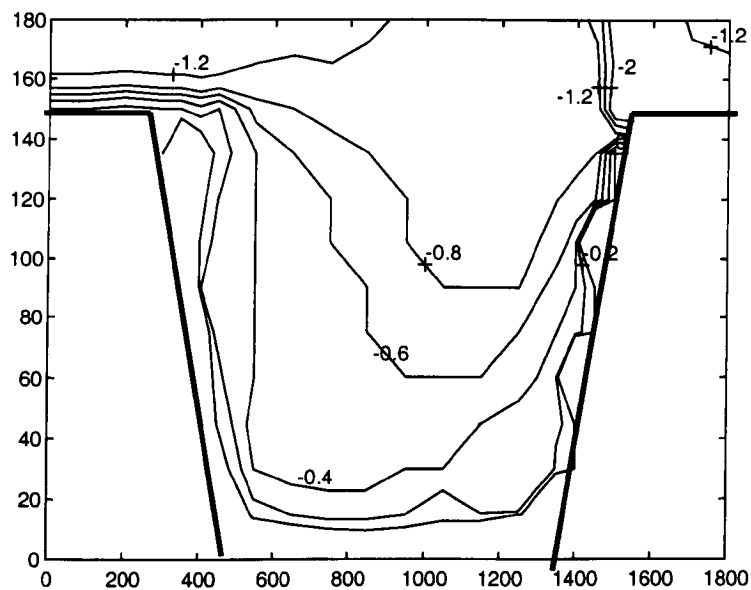




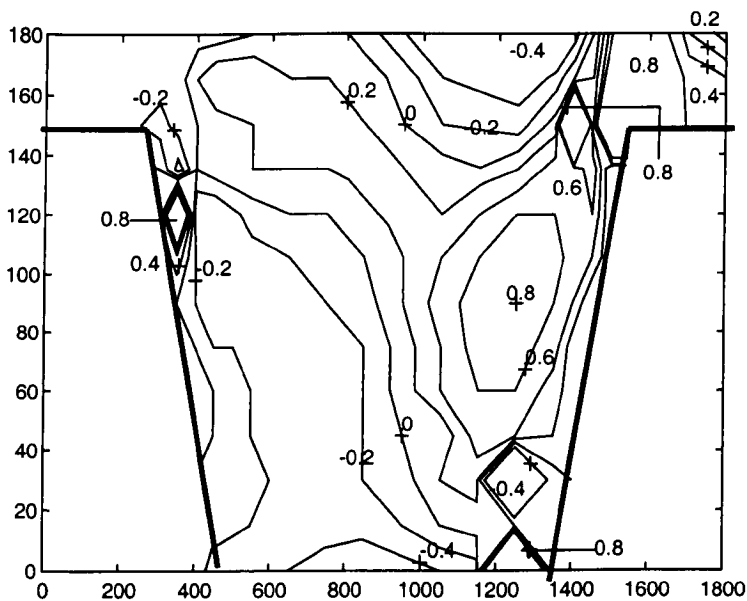
**Fig. 5.34 –Difference in Velocity at Cross-Section 8 between CFX FCF-1 and FCF-3 (cm/s)**



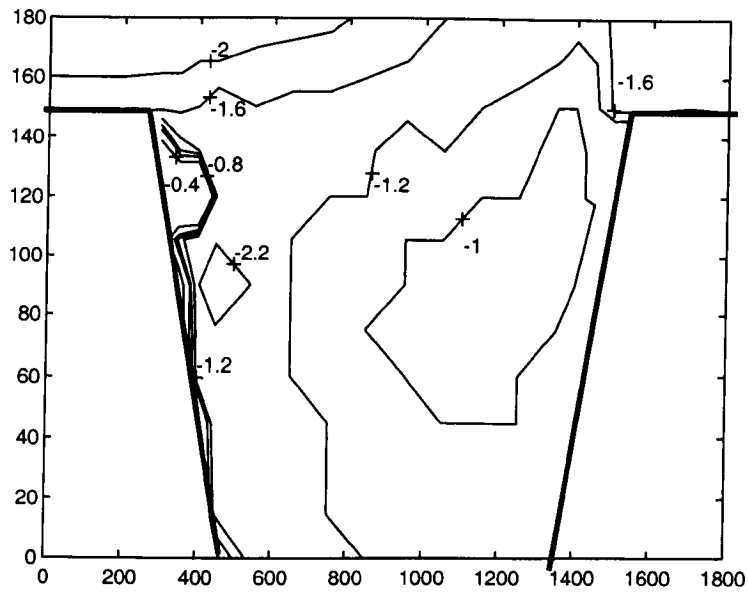
**Fig. 5.35 –Difference in Angle at Cross-Section 8 between CFX FCF-1 and FCF-3 (deg.)**



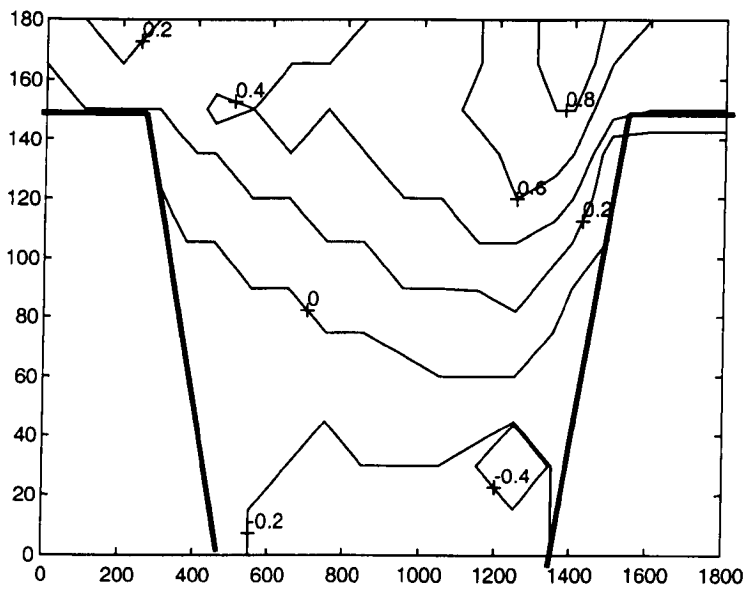
**Fig. 5.36 –Difference in Velocity at Cross-Section 8 between CFX FCF-2 and FCF-3 (cm/s)**



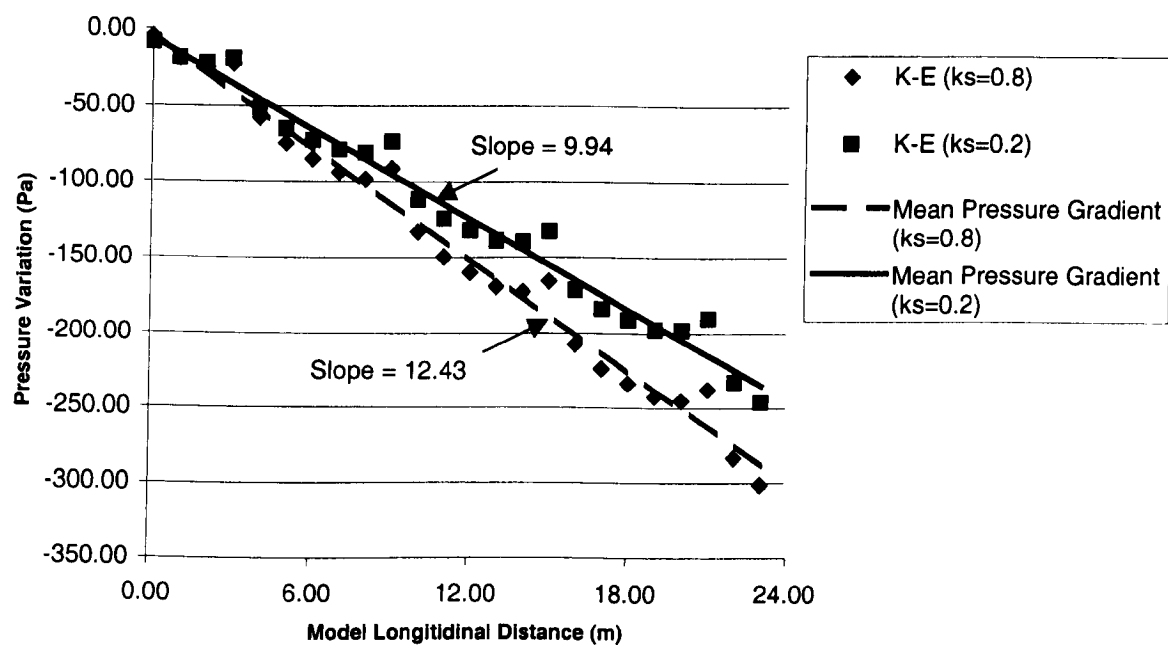
**Fig. 5.37 –Difference in Angle at Cross-Section 8 between CFX FCF-2 and FCF-3 (deg.)**



**Fig. 5.38 –Difference in Velocity at Cross-Section 8 between Model using an I/O Boundary Condition and a Model using Periodic Boundary Conditions (FCF-2)**



**Fig. 5.39 –Difference in Angle at Cross-Section 8 between Model using an I/O Boundary Condition and a Model using Periodic Boundary Conditions (FCF-2)**



**Fig. 5.40 – Sensitivity Analysis for the CFX Model of FCF B23 Experiment:  
Variation of the Pressure Slope with Roughness**

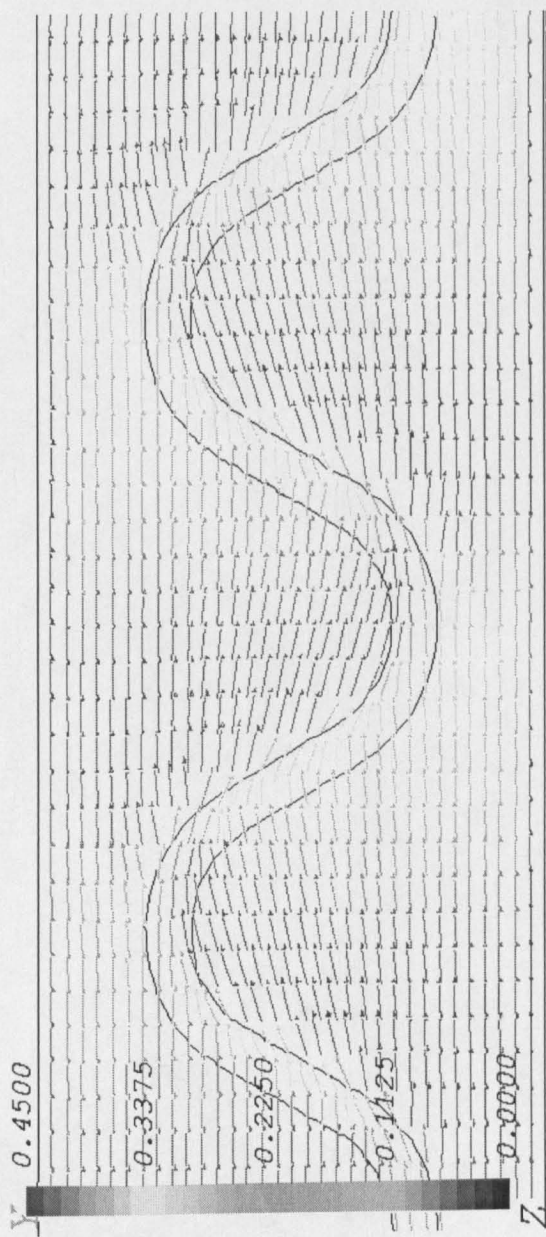
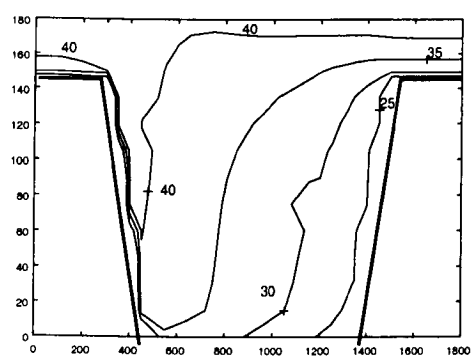
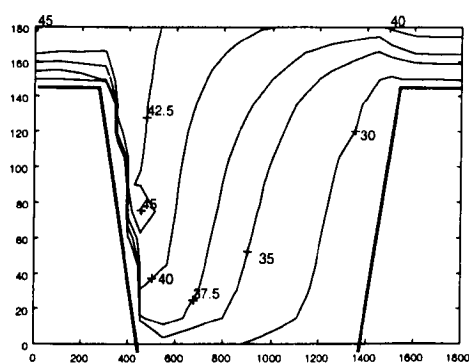


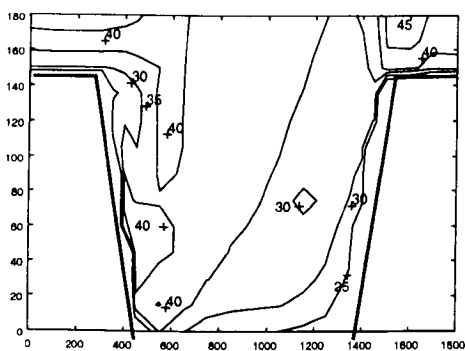
Fig. 5.41 – CFX Surface Velocity for FCF B23 Experiment ( $k_s = 0.2$  mm, Mesh FCF-2,  $k-\varepsilon$  Model)



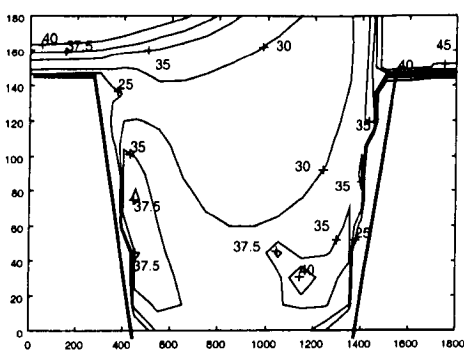
Cross-Section 1



Cross-Section 3

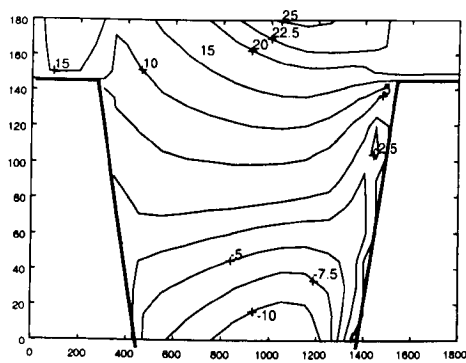


Cross-Section 5

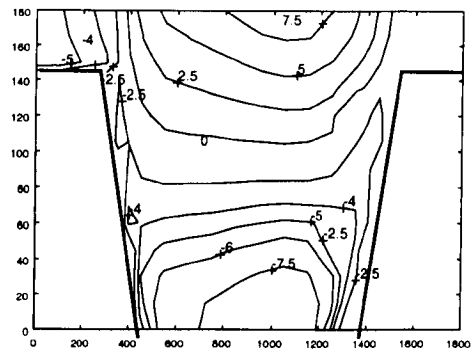


Cross-Section 8

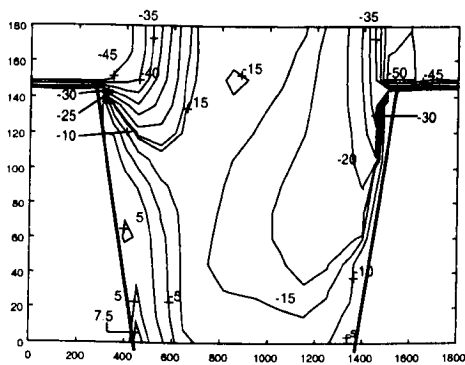
**Fig. 5.42 – FCF B23 CFX Velocity Norm Predictions (cm/s) at Cross-Sections 1, 3, 5 and 8 ( $k_s = 0.8$  mm, Grid FCF-3,  $k-\epsilon$  Model)**



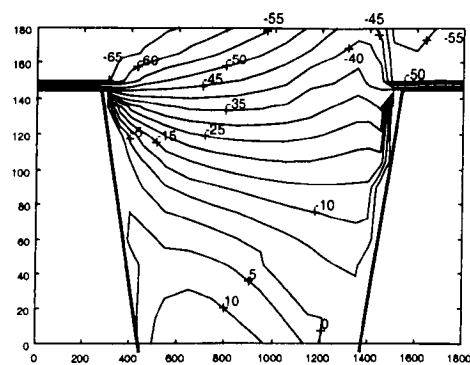
Cross-Section 1



Cross-Section 3

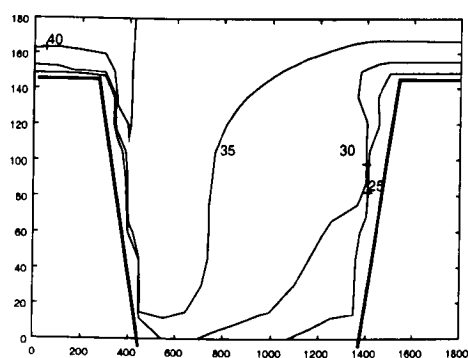


Cross-Section 5

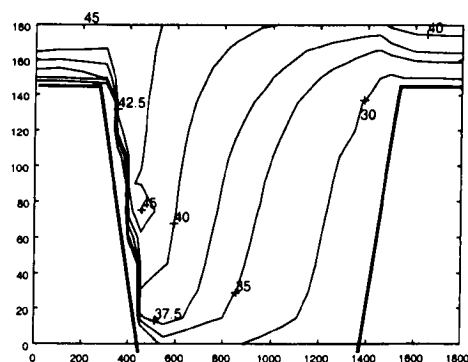


Cross-Section 8

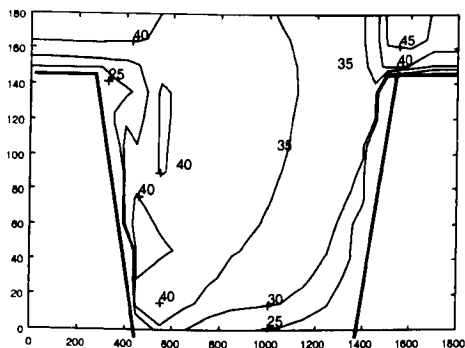
**Fig. 5.43 - FCF B23 CFX Velocity Angle Predictions (deg.) at Cross-Sections 1, 3, 5 and 8 ( $k_s = 0.8$  mm, Grid FCF-3,  $k-\epsilon$  Model)**



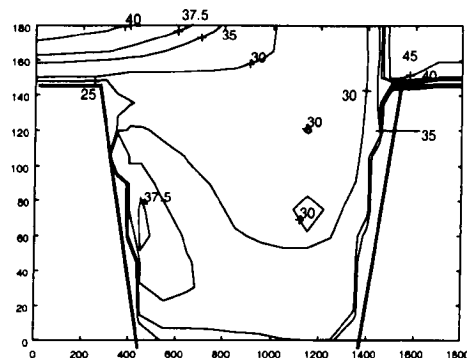
Cross-Section 1



Cross-Section 3



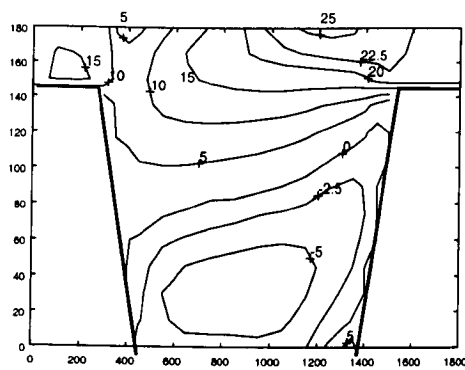
Cross-Section 5



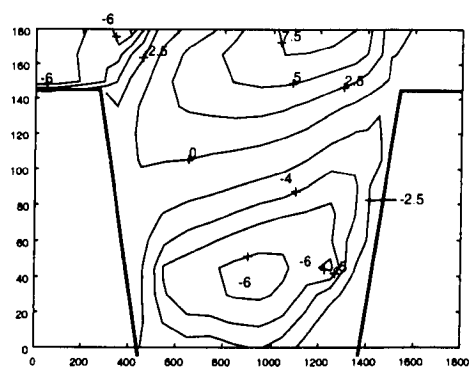
Cross-Section 8

**Fig. 5.44 – FCF B23 CFX Velocity Norm Predictions (cm/s) at Cross-Sections 1, 3, 5 and 8 ( $k_s = 0.8$  mm, Grid FCF-3, RSM Model)**

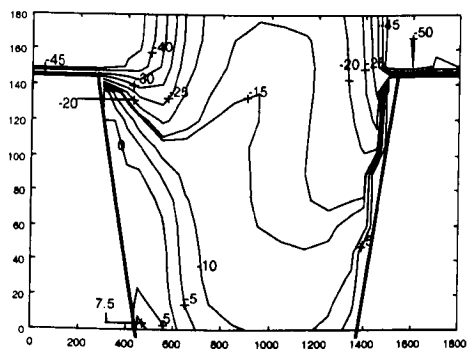




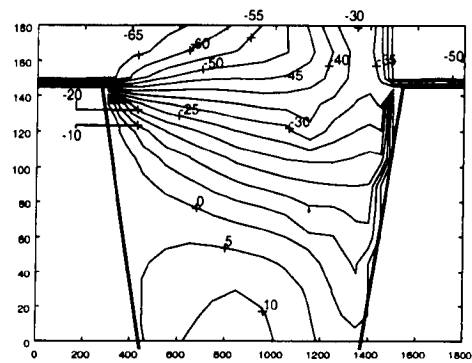
Cross-Section 1



Cross-Section 3

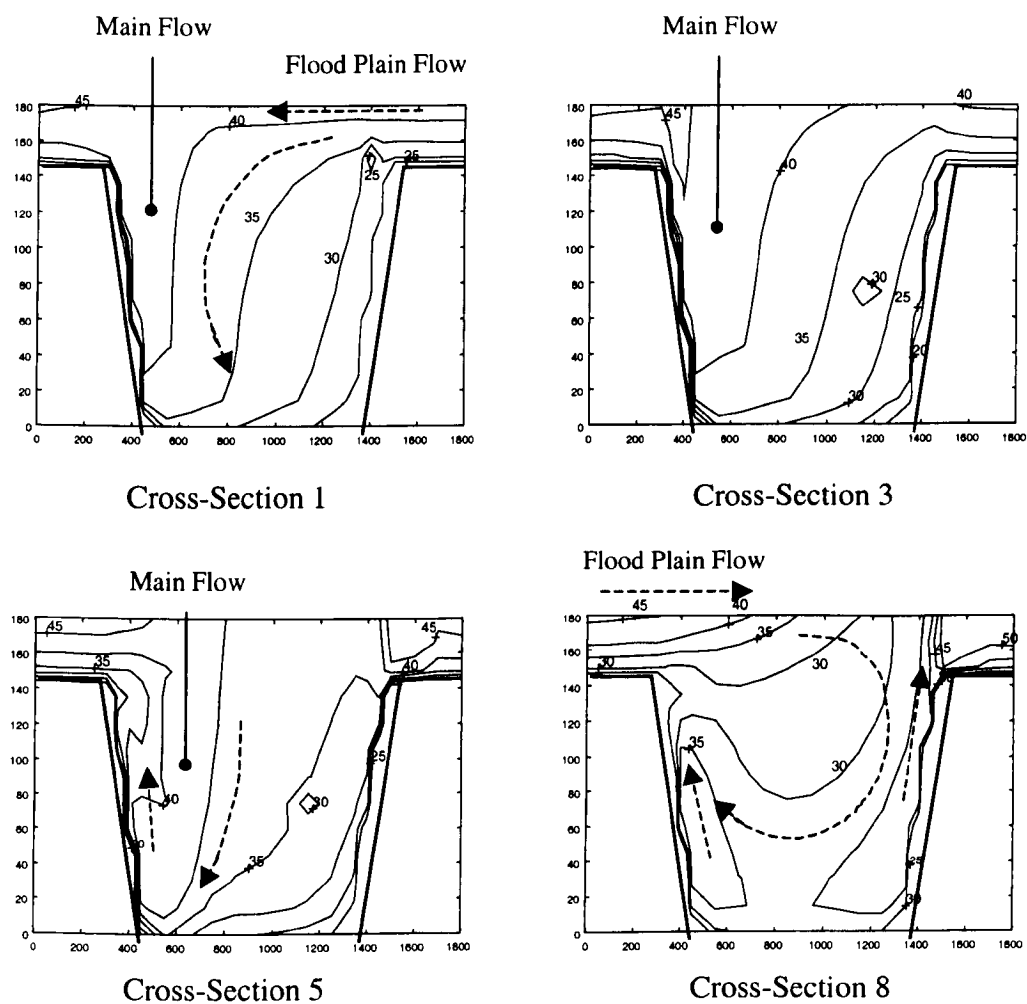


Cross-Section 5

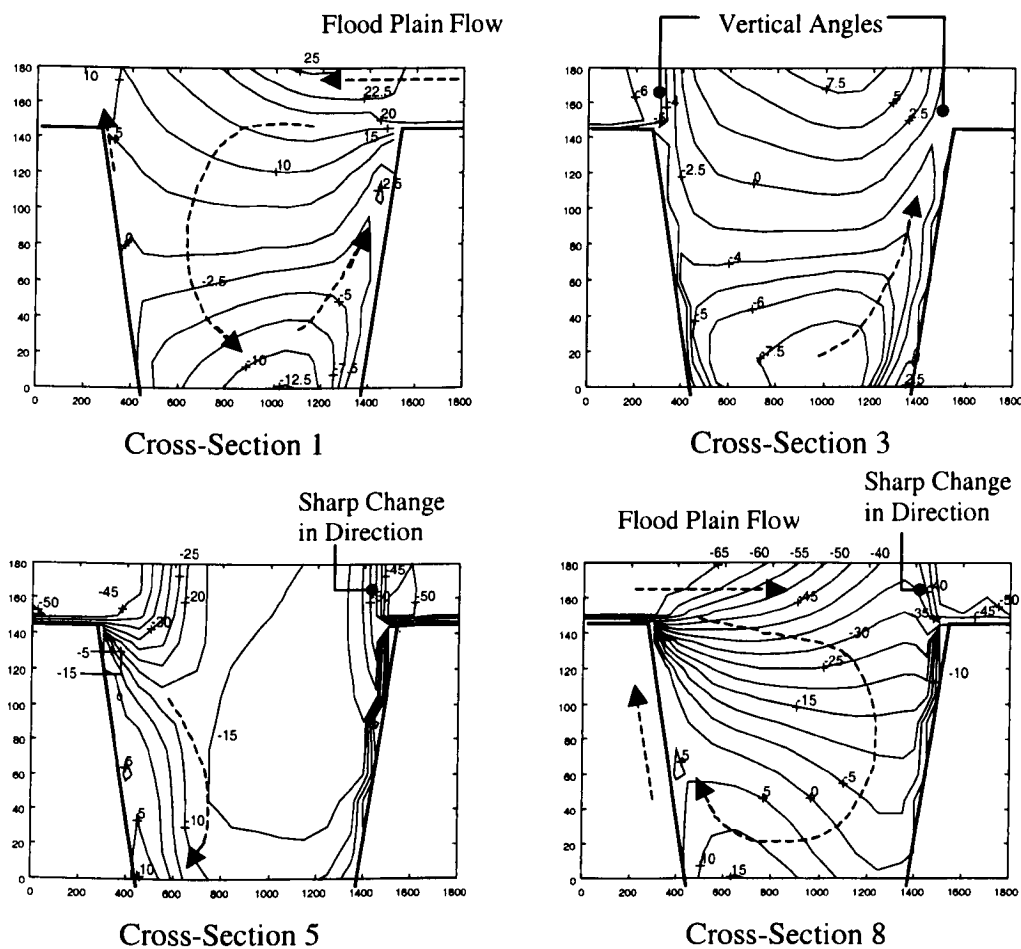


Cross-Section 5

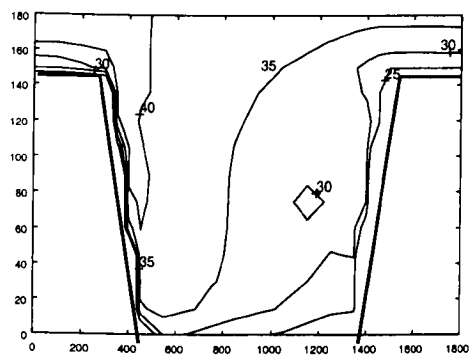
**Fig. 5.45 – FCF B23 CFX Velocity Angle Predictions (deg.) at Cross-Sections 1, 3, 5 and 8 ( $k_s = 0.8$  mm, Grid FCF-3, RSM Model)**



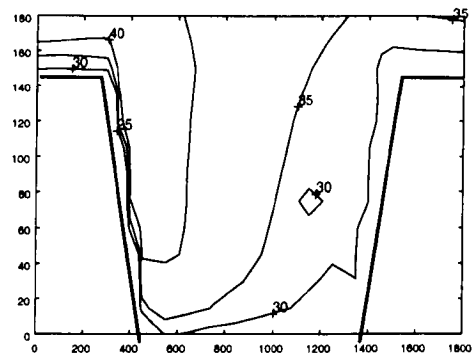
**Fig. 5.46 – FCF B23 CFX Velocity Norm Predictions (cm/s) at Cross-Sections 1, 3, 5 and 8 ( $k_s = 0.2$  mm, Grid FCF-3,  $k-\varepsilon$  Model)**



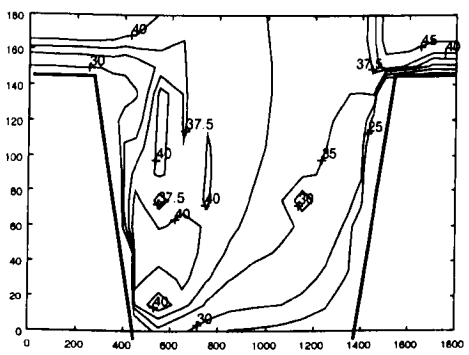
**Fig. 5.47 - FCF B23 CFX Velocity Angle Predictions (deg.) at Cross-Sections 1, 3, 5 and 8 ( $k_s = 0.2$  mm, Grid FCF-3, RSM)**



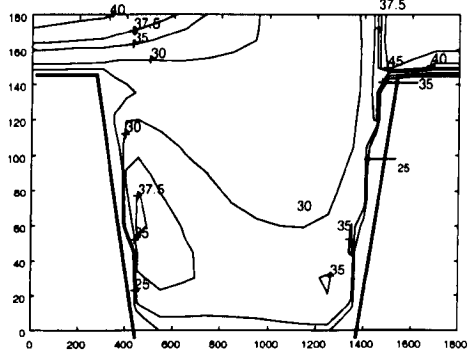
Cross-Section 1



Cross-Section 3

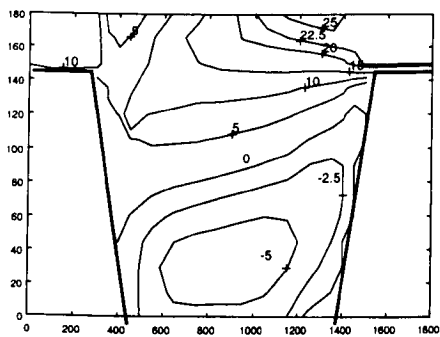


Cross-Section 5

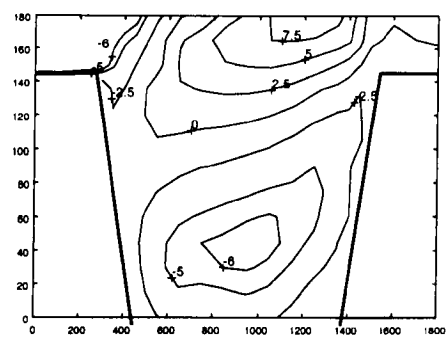


Cross-Section 8

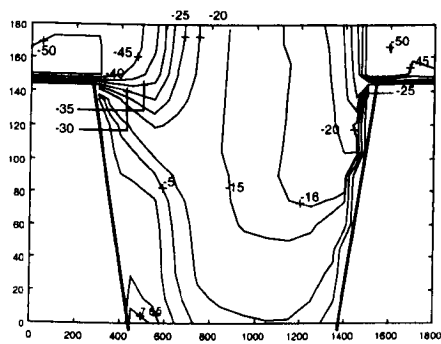
**Fig. 5.48 – FCF B23 CFX Velocity Norm Predictions (cm/s) at Cross-Sections 1, 3, 5 and 8 ( $k_s = 0.2$  mm, Grid FCF-3, RSM)**



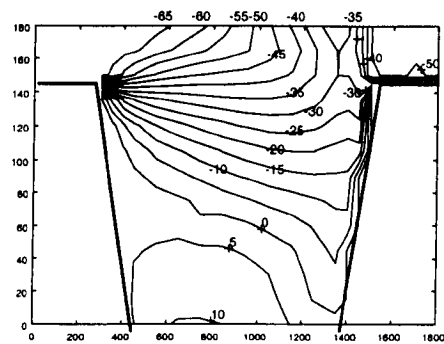
Cross-Section 1



Cross-Section 3

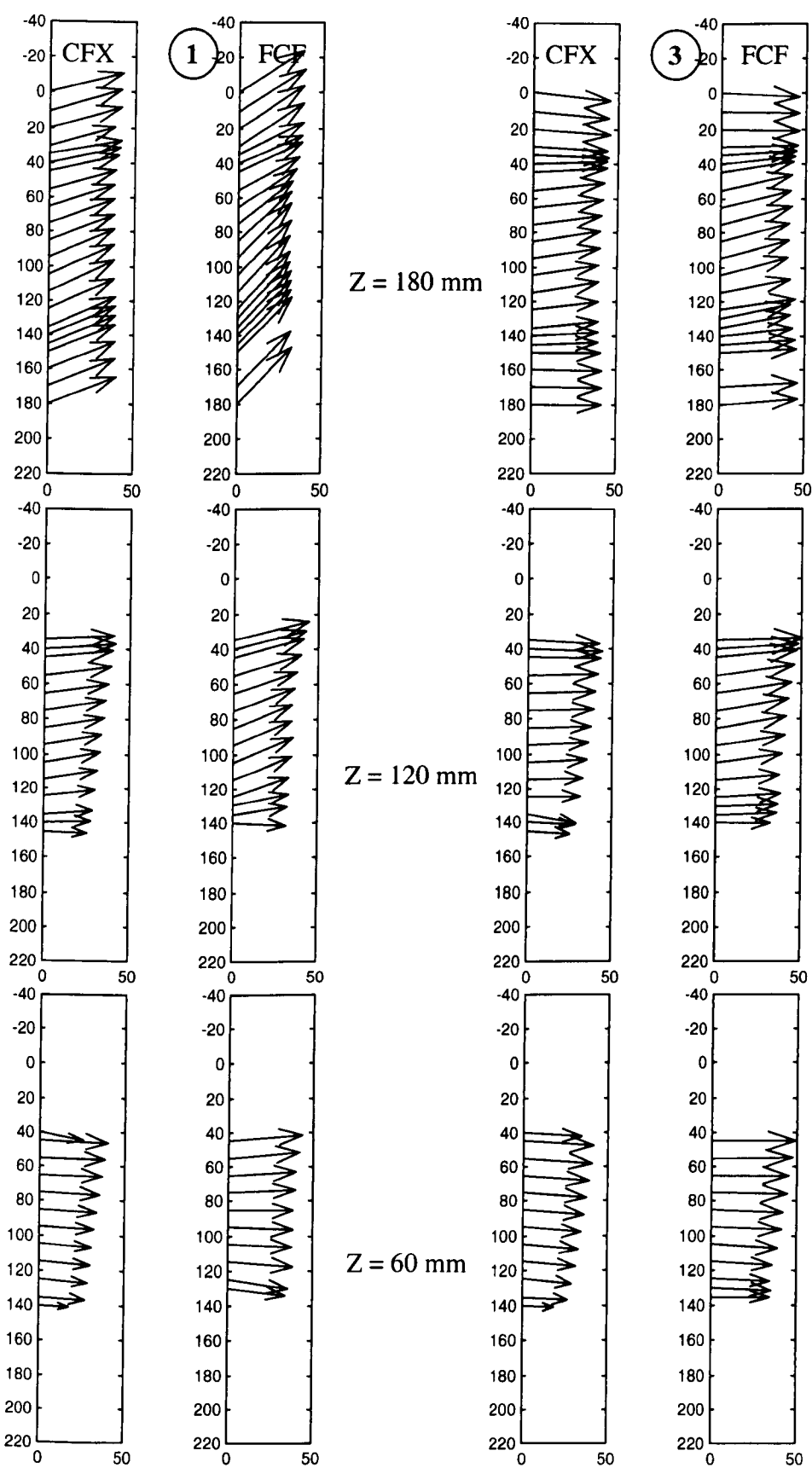


Cross-Section 5

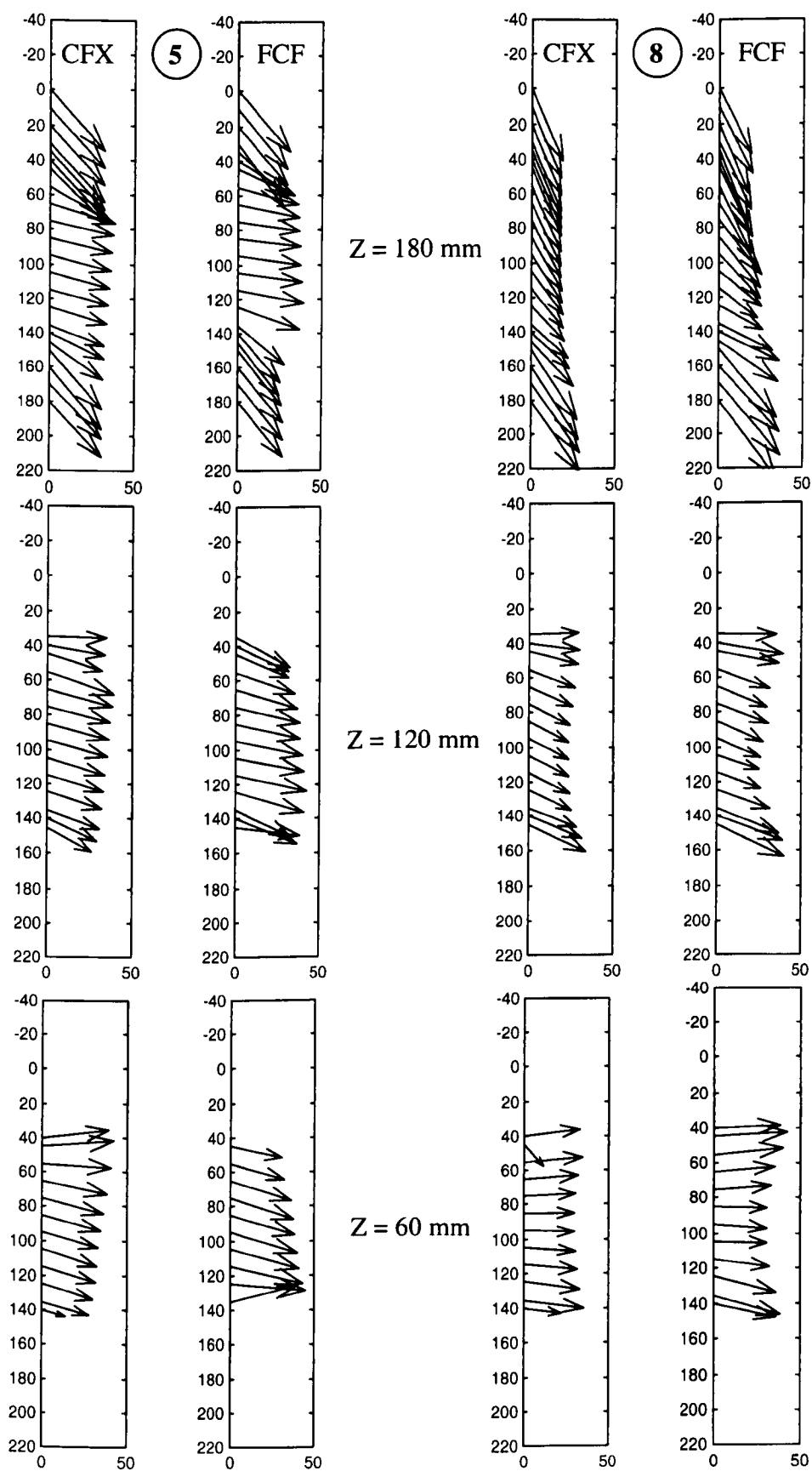


Cross-Section 8

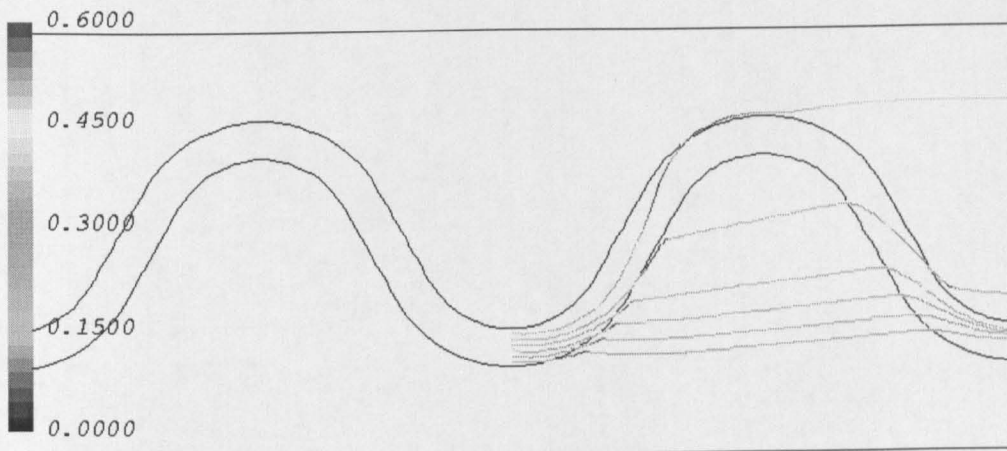
**Fig. 5.49 - FCF B23 CFX Velocity Angle Predictions (deg.) ay Cross-Sections 1, 3, 5 and 8 ( $k_s = 0.2$  mm, Grid FCF-3, RSM)**



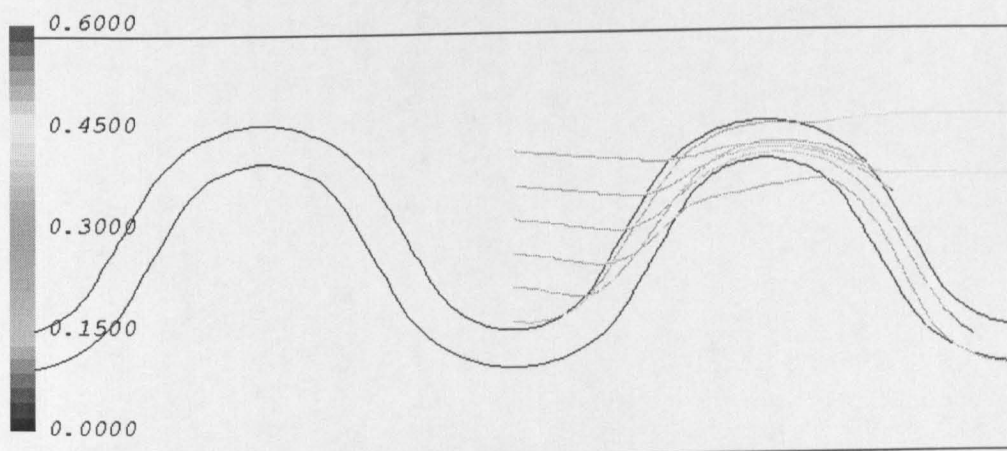
**Fig. 5.50 – Velocity Vectors at Depth 60, 120 and 180 mm at FCF Sections 1 and 3**



**Fig. 5.51– Velocity Vectors at Depth 60, 120 and 180 mm at FCF Sections 5 and 8**



(a)



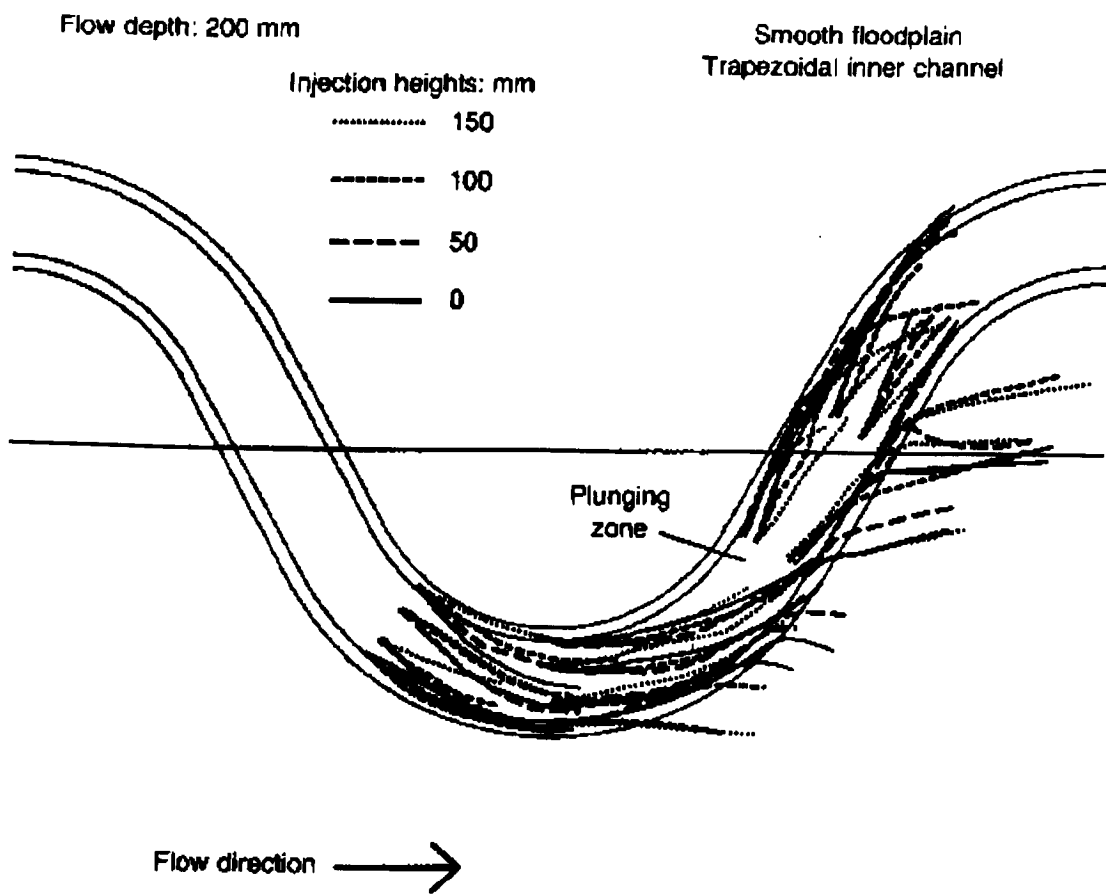
(b)

**Fig. 5.52 – FCF B23 CFX Numerical Tracer Experiment:**

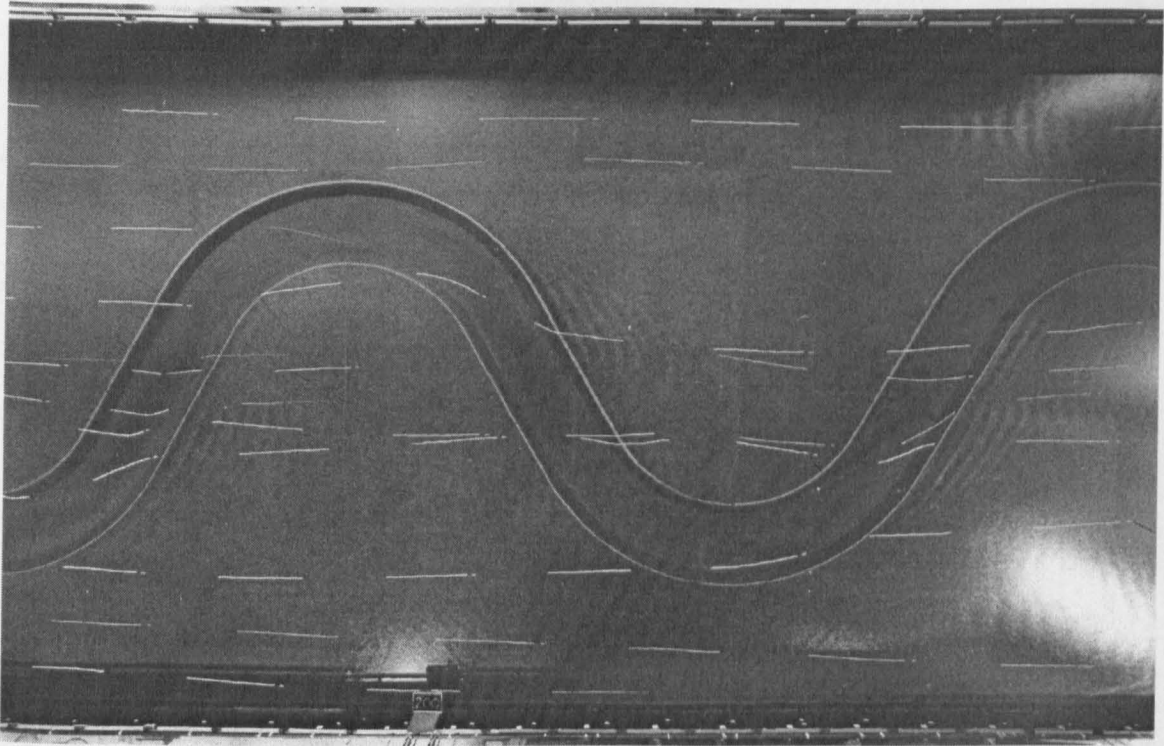
**(a) Release in Main Channel at Mid-Depth (100 mm)**

**(b) Release on the Floodplain at Mid-Depth (175 mm)**

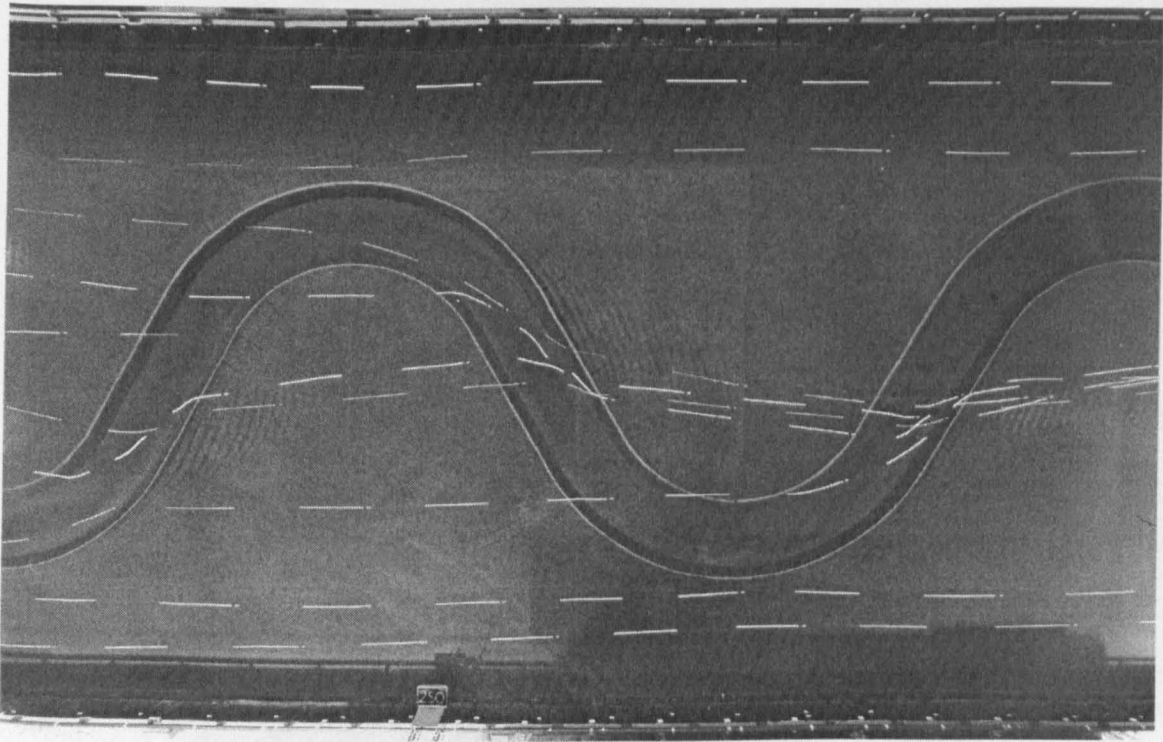




**Fig. 5.53 – Tracer Experimental Data in FCF B23**  
(after Willetts and Hardwick, 1993)

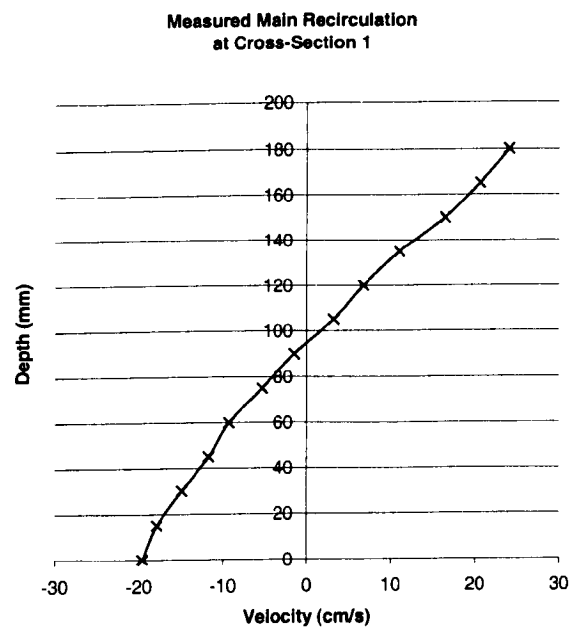
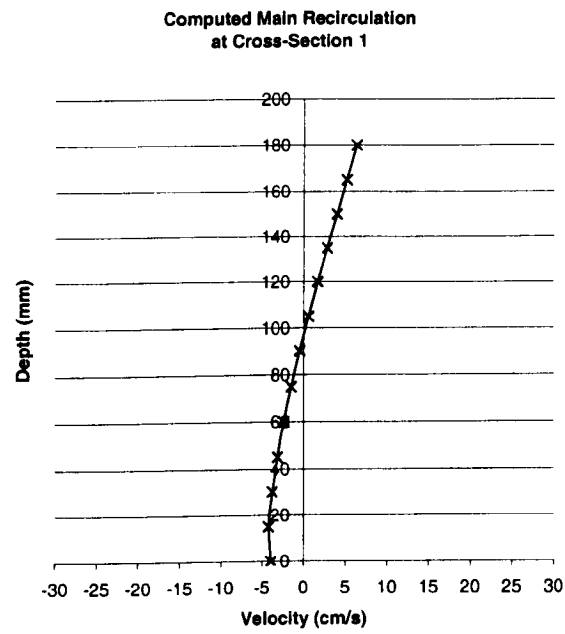


(a)

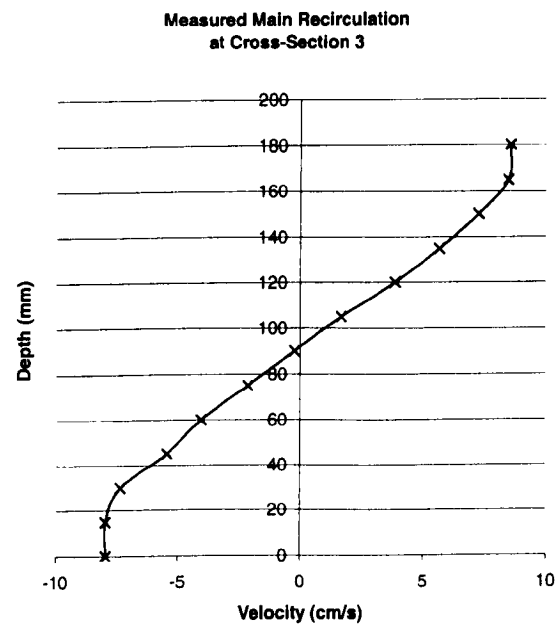
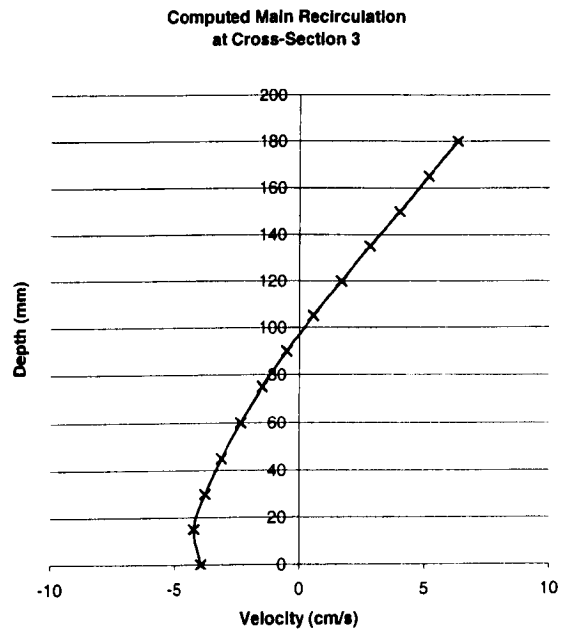


(b)

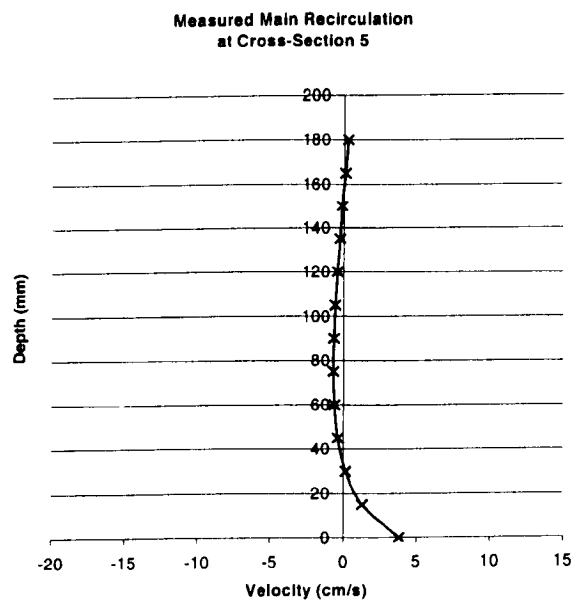
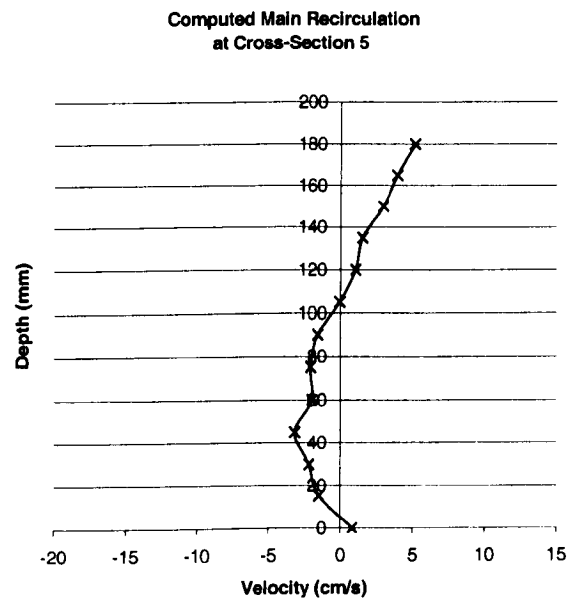
**Fig. 5.54 – Surface Tracer Experiment Photographs in FCF Series B:**  
**(a)  $Dr = 0.25$ , (b)  $Dr = 0.40$**   
(Courtesy of Professor Ervine, Univ. of Glasgow)



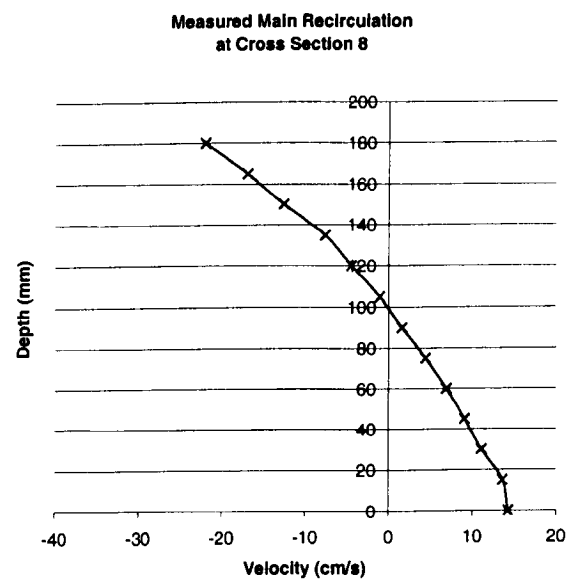
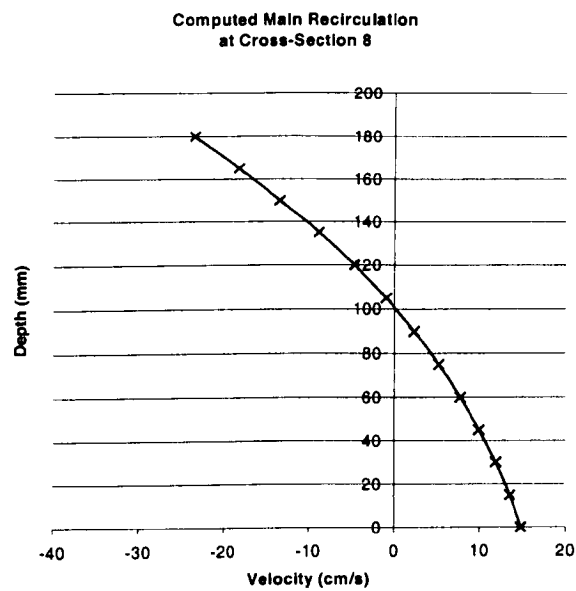
**Fig. 5.55 – FCF B23 CFX Model: Recirculation at Cross-Section 1**



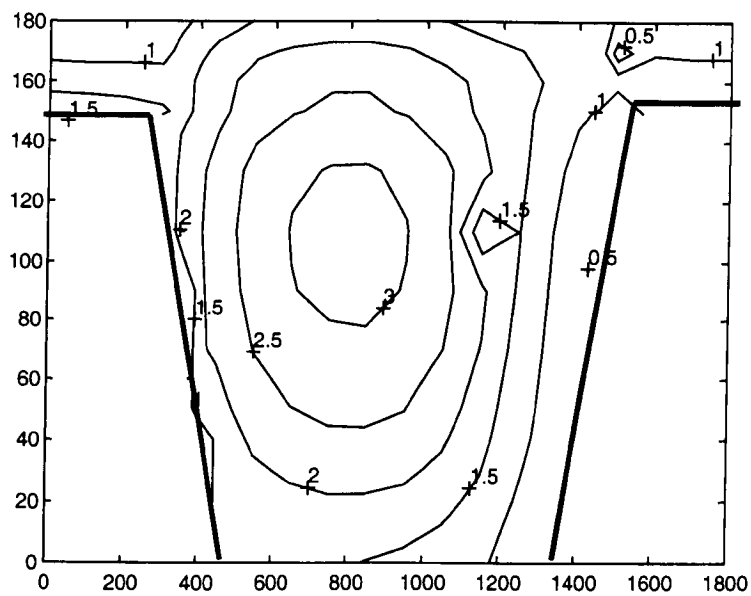
**Fig. 5.56 – FCF B23 CFX Model: Recirculation at Cross-Section 3**



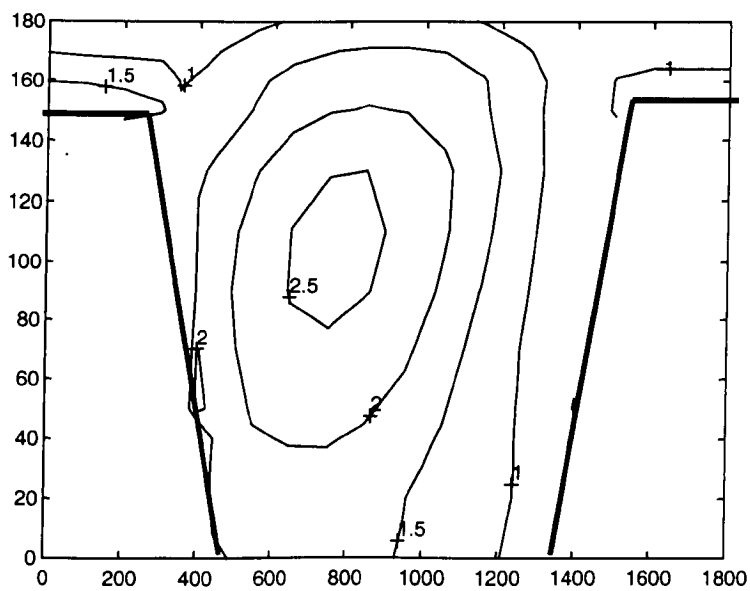
**Fig. 5.57 – FCF B23 CFX Model: Recirculation at Cross-Section 5**



**Fig. 5.59 – FCF B23 CFX Model: Recirculation at Cross-Section 8**



(a)

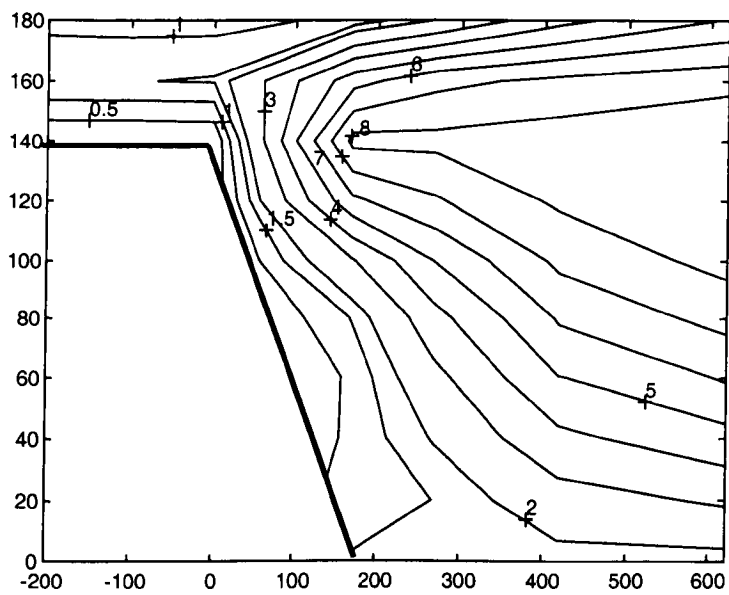


(b)

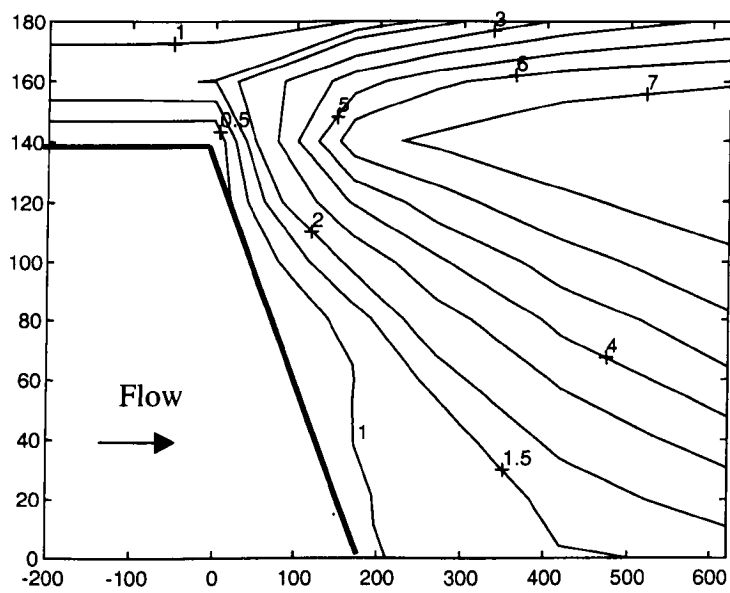
**Fig. 5.60 - CFX Predicted Turbulence Kinetic Energy**  
**( $\times 10^{-3} \text{ m}^2/\text{s}^2$ ) at Cross-Section 3:**

**(a)  $k-\varepsilon$  Model**

**(b) RSM**



(a)



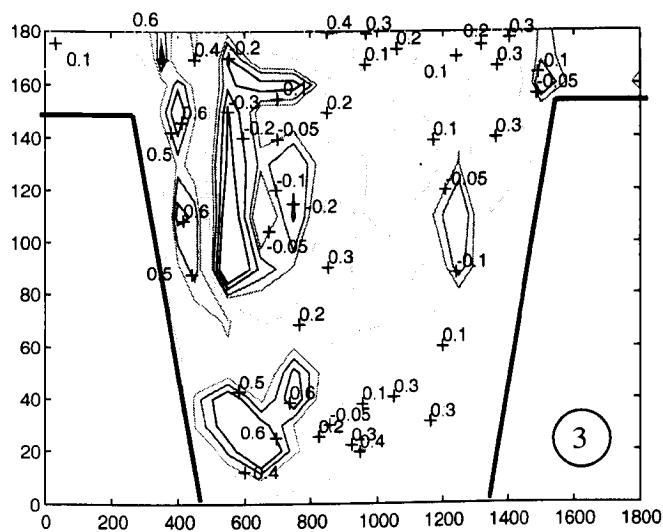
(b)

**Fig. 5.61 – CFX Predicted Turbulence Kinetic Energy**  
**( $\times 10^{-3} \text{ m}^2/\text{s}^2$ ) at Cross-Section 8b:**

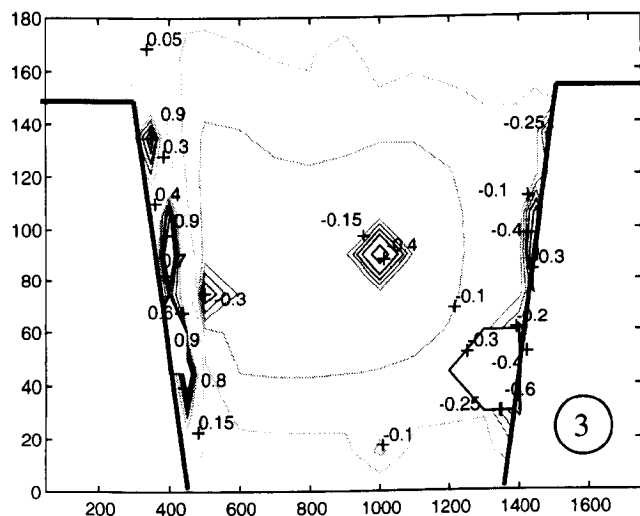
**(a)  $k-\varepsilon$  Model**

**(b) RSM**

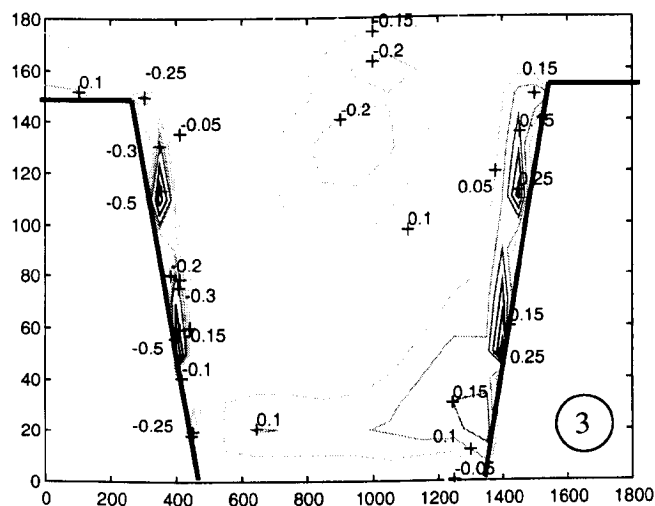




FCF Turbulence Data at  
Cross-Section 3:  $T_{yx}$  (N/m<sup>2</sup>)

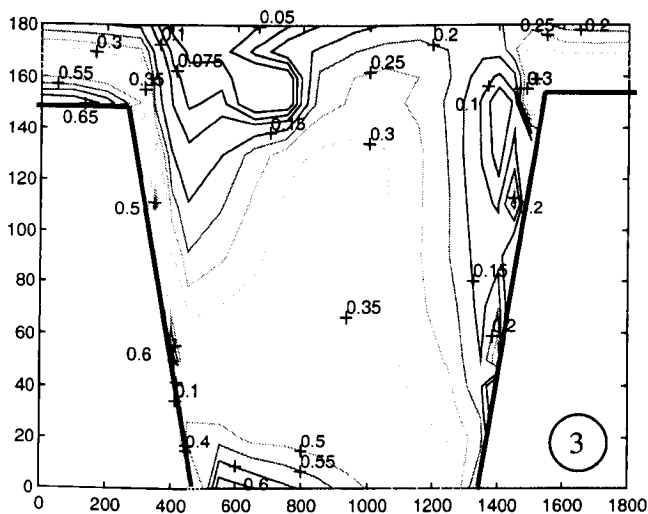
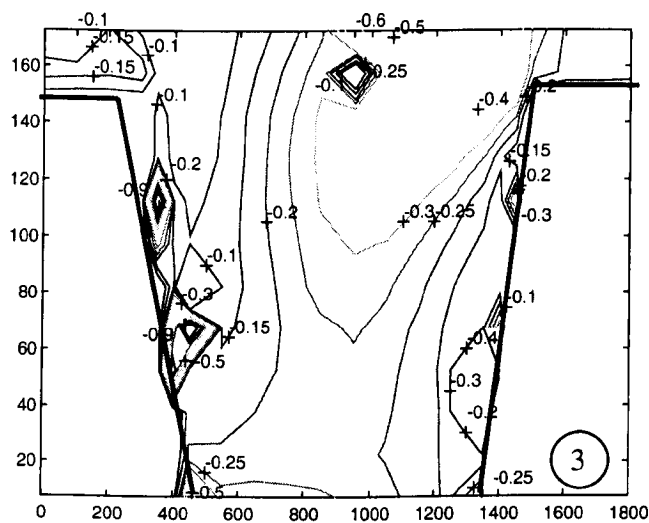
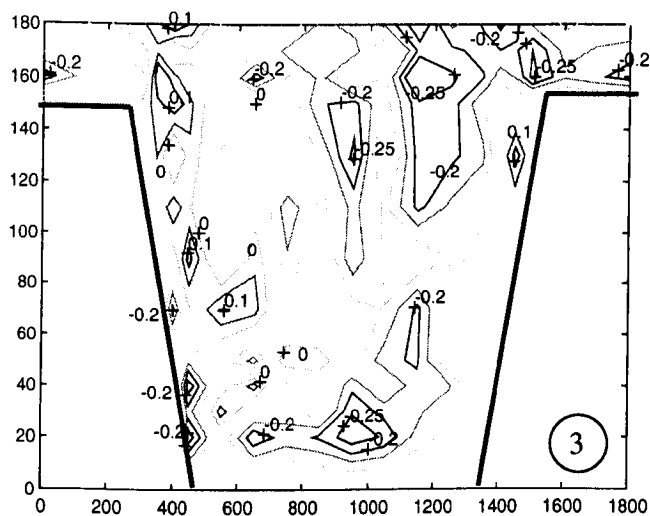


Processed  $T_{yx}$  (N/m<sup>2</sup>) at  
Cross-Section 3, using CFX  
 $k-\epsilon$  Data

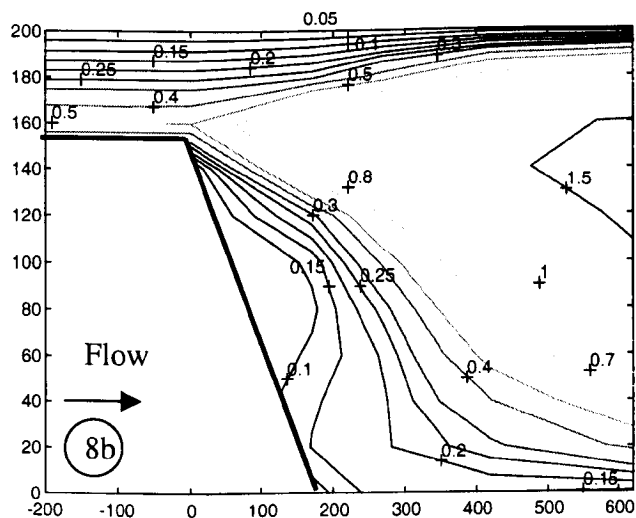
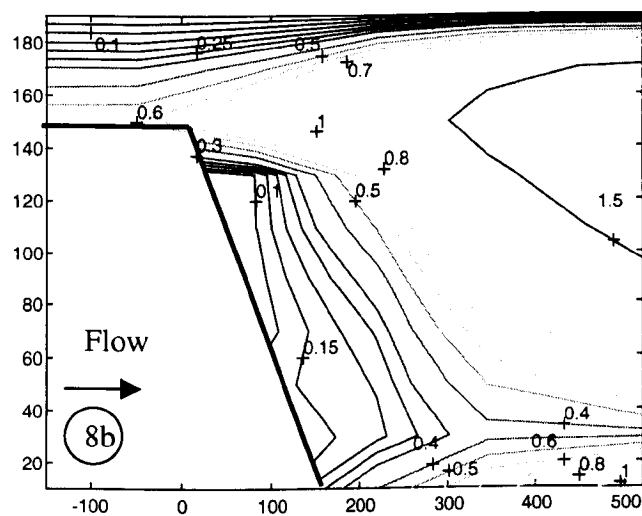
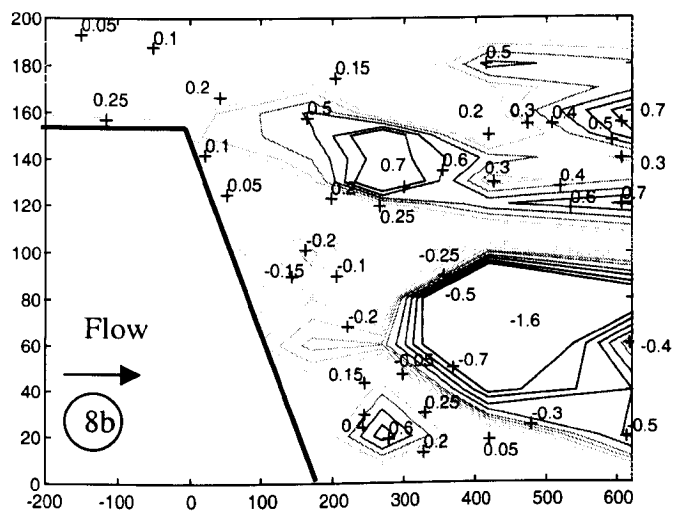


Calculated  $T_{yx}$  (N/m<sup>2</sup>) at  
Cross-Section 3 with RSM

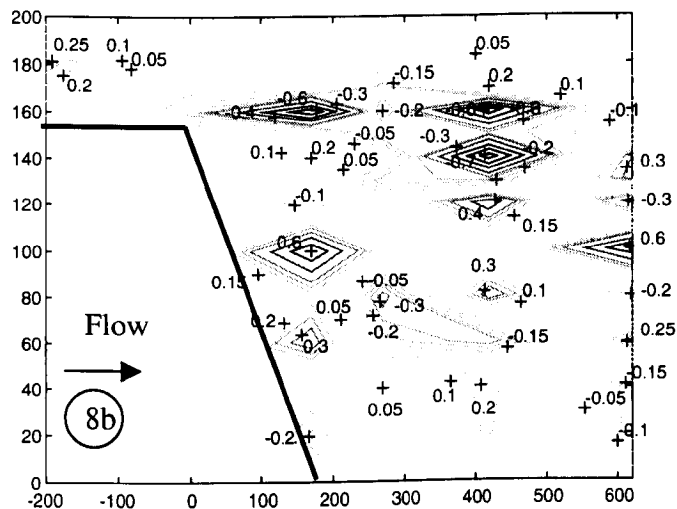
**Fig. 5.62 – Comparison of  $T_{yx}$  (N/m<sup>2</sup>) at Cross-Section 3**



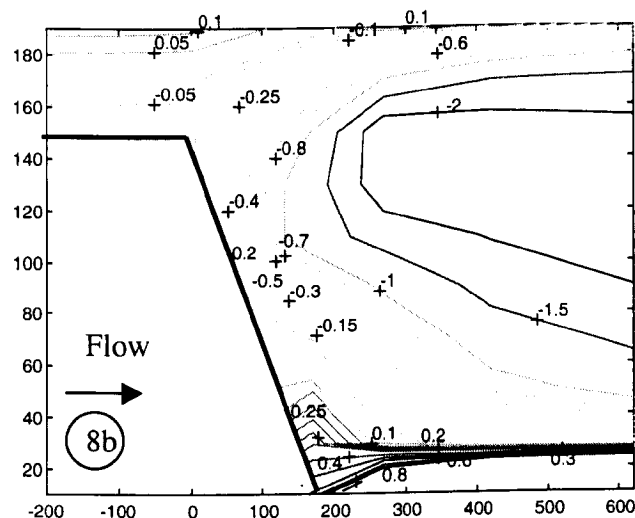
**Fig. 5.63 - Comparison of  $T_{zx}$  (N/m<sup>2</sup>) at Cross-Section 3**



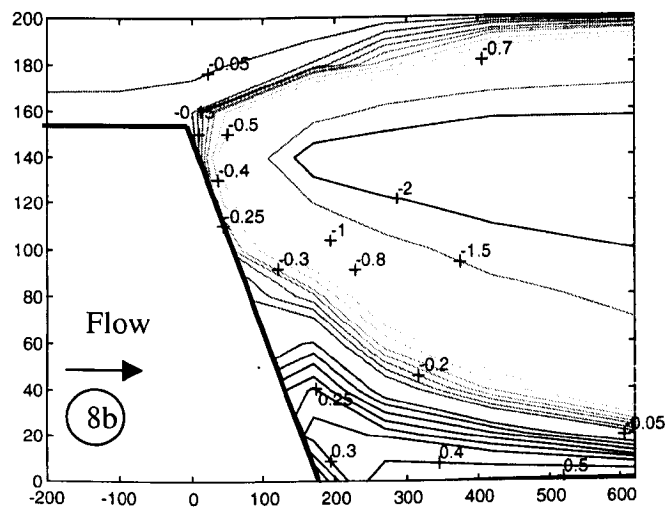
**Fig. 5.64 - Comparison of  $T_{zx}(N/m^2)$  at the Cross-Over**



FCF Turbulence Data at the Cross-Over:  $T_{yx}(N/m^2)$

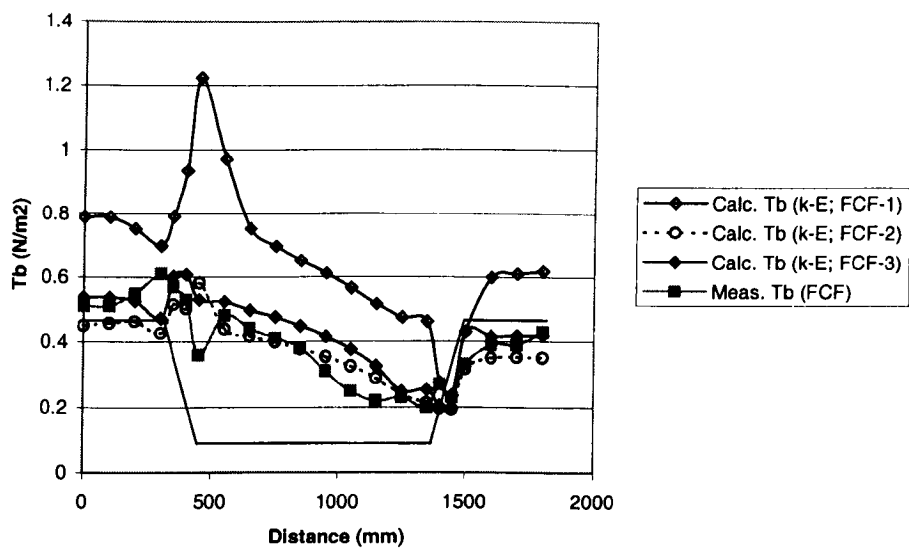


Processed  $T_{yz}(N/m^2)$  at the Cross-Over, using  $k-\epsilon$  Data

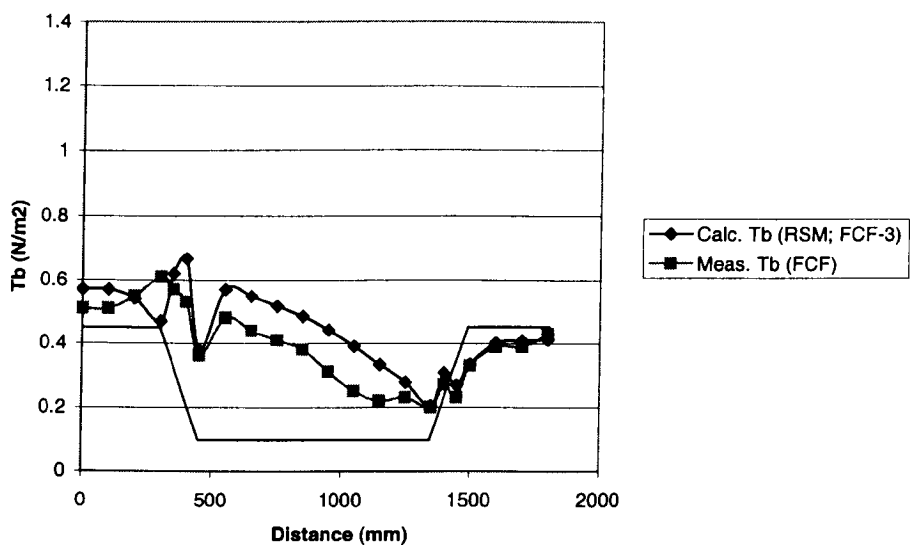


Calculated  $T_{yz}(N/m^2)$  at the Cross-Over with RSM

Fig. 5.65 - Comparison of  $T_{yz}(N/m^2)$  at the Cross-Over

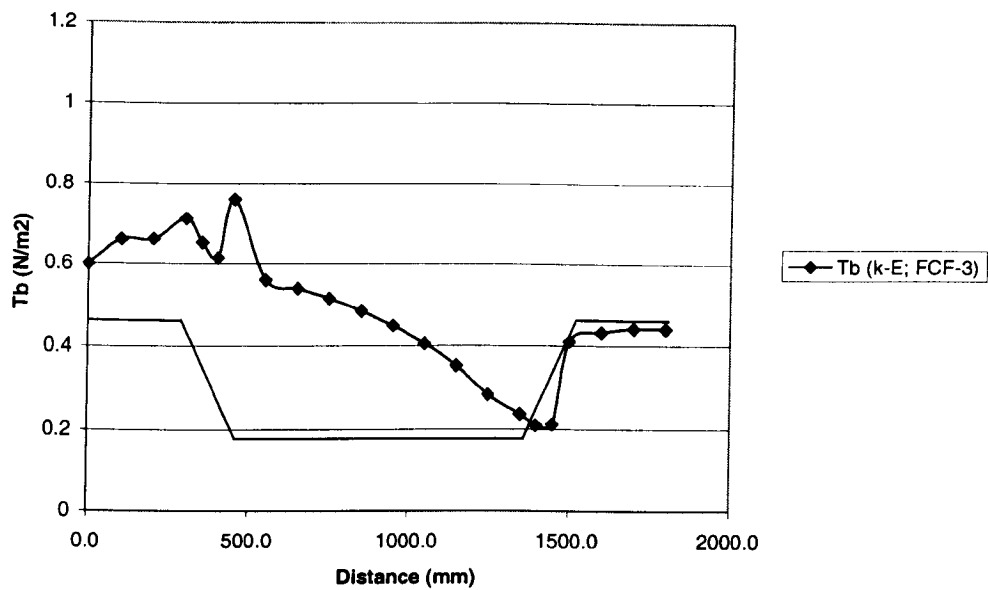


(a)

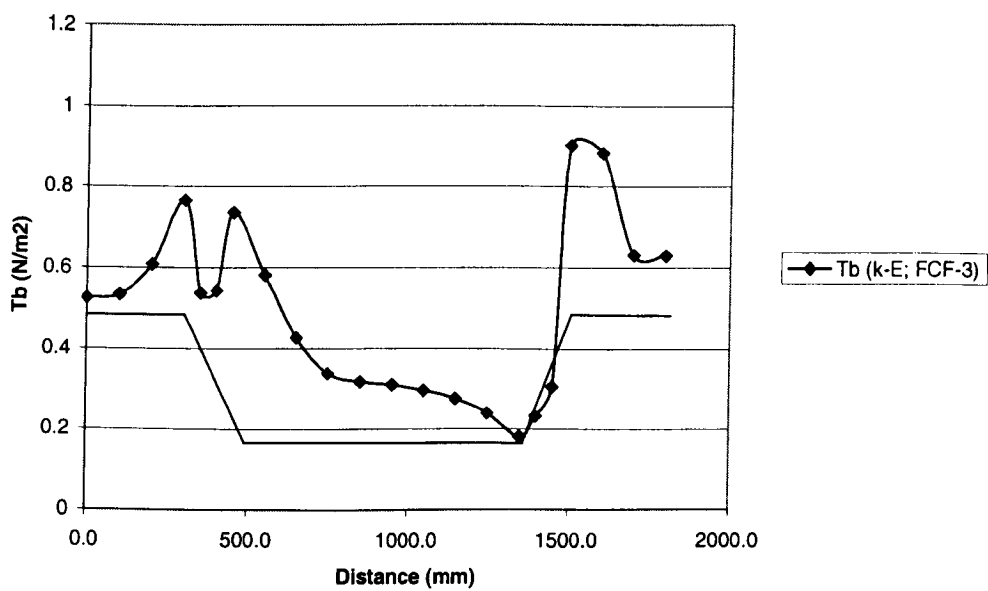


(b)

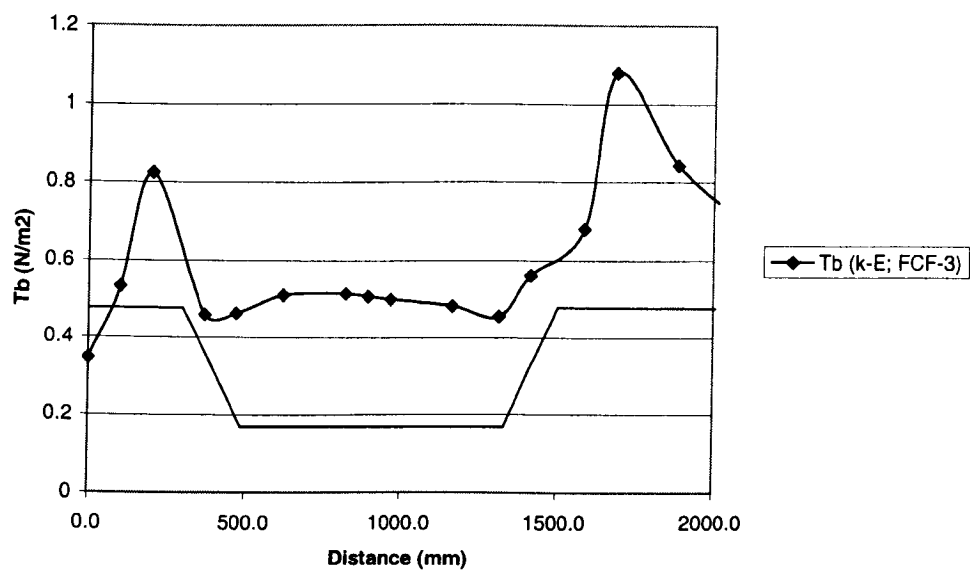
**Fig. 5.66 – Comparison of Bed Shear Stress Profiles at Cross-Section 3 from CFX FCF B23 Model:**  
**(a) with  $k-\varepsilon$  turbulence model;**  
**(b) with LRR-RSM.**



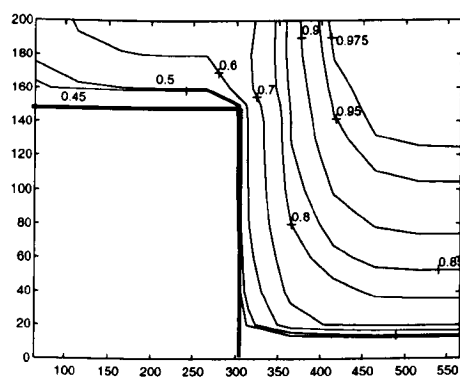
**Fig. 5.67 – Calculated Bed Shear Stress Profile at Cross-Section 1 from CFX FCF B23 Model**



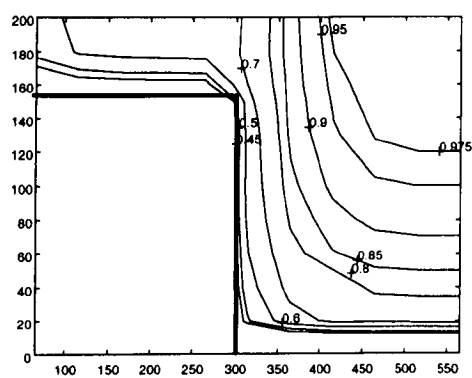
**Fig. 5.68 – Calculated Bed Shear Stress Profile at Cross-Section 5 from CFX FCF B23 Model**



**Fig. 5.69 – Calculated Bed Shear Stress Profile at Cross-Section 8 from CFX FCF B23 Model**



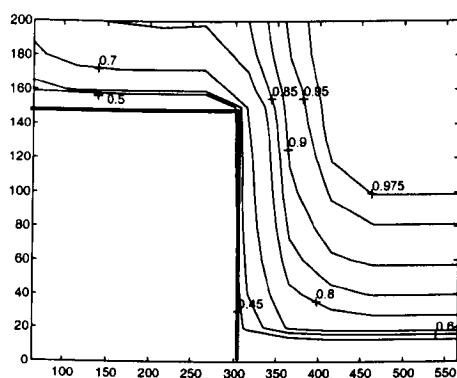
(a)



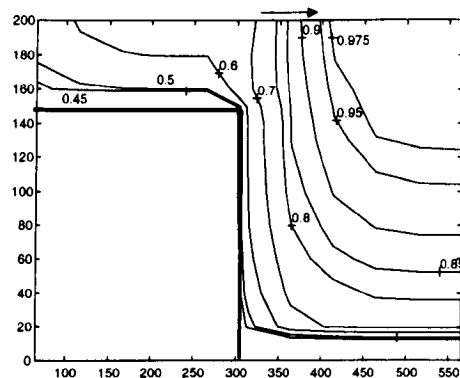
(b)

**Fig. 5.70 – Comparison of Velocity Profile in Tominaga’s Model  
For Different Grid Resolutions (54,000 and 109,200 Elements)**





(a)

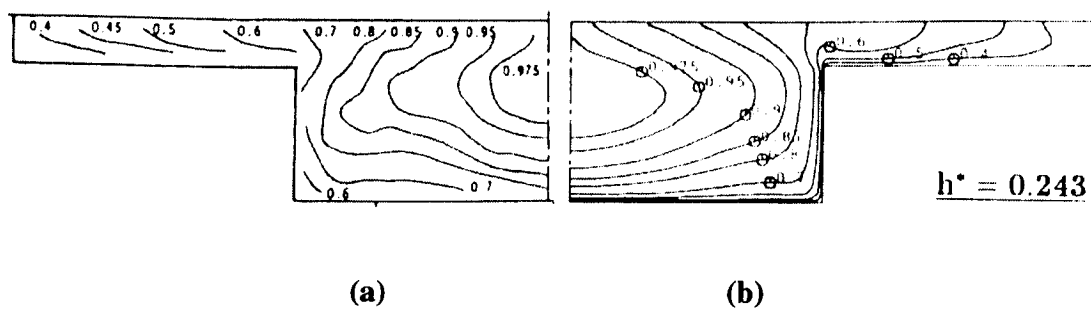


(b)

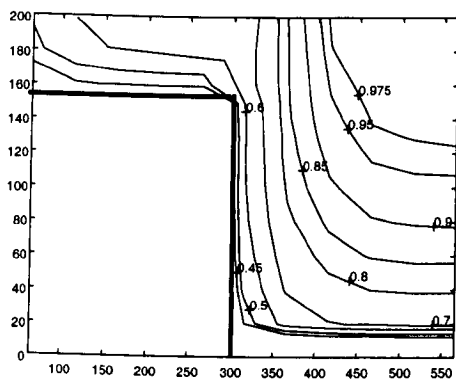
**Fig. 5.71 – Predicted Velocity Profiles in Tominaga’s Experiment (CFX):**

**(a)  $k-\varepsilon$  Model**

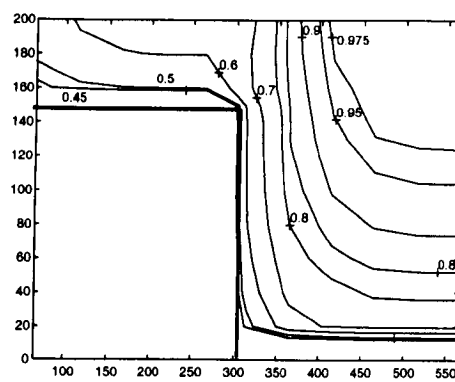
**(b) LRR-RSM**



**Fig. 5.72 – Tominaga's Experiment Results:**  
**(a) Laboratory Data (Tominaga et al., 1989)**  
**(b) LRR-RSM Numerical Model (Cokljat, 1993)**



(a)



(b)

**Fig. 5.73 – Impact of Reynolds Number in Tominaga’s Experiment (CFX):**

**(a)  $Re = 3.5 \times 10^4$**

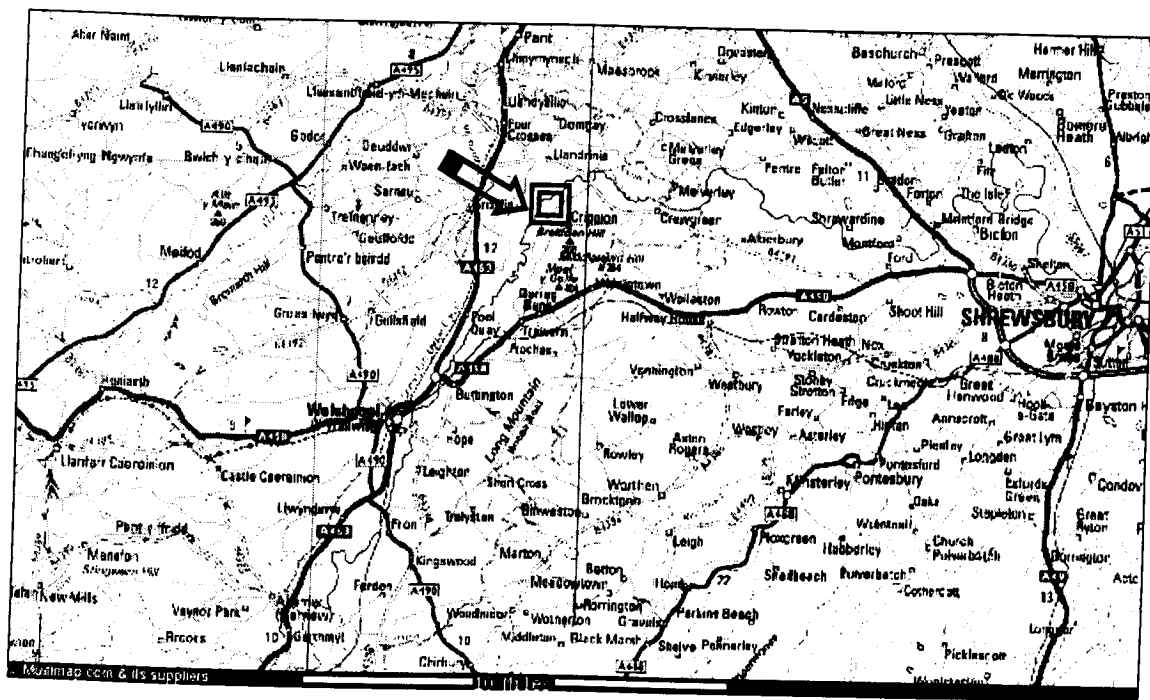
**(b)  $Re = 7.0 \times 10^4$**

# **Chapter 6:**

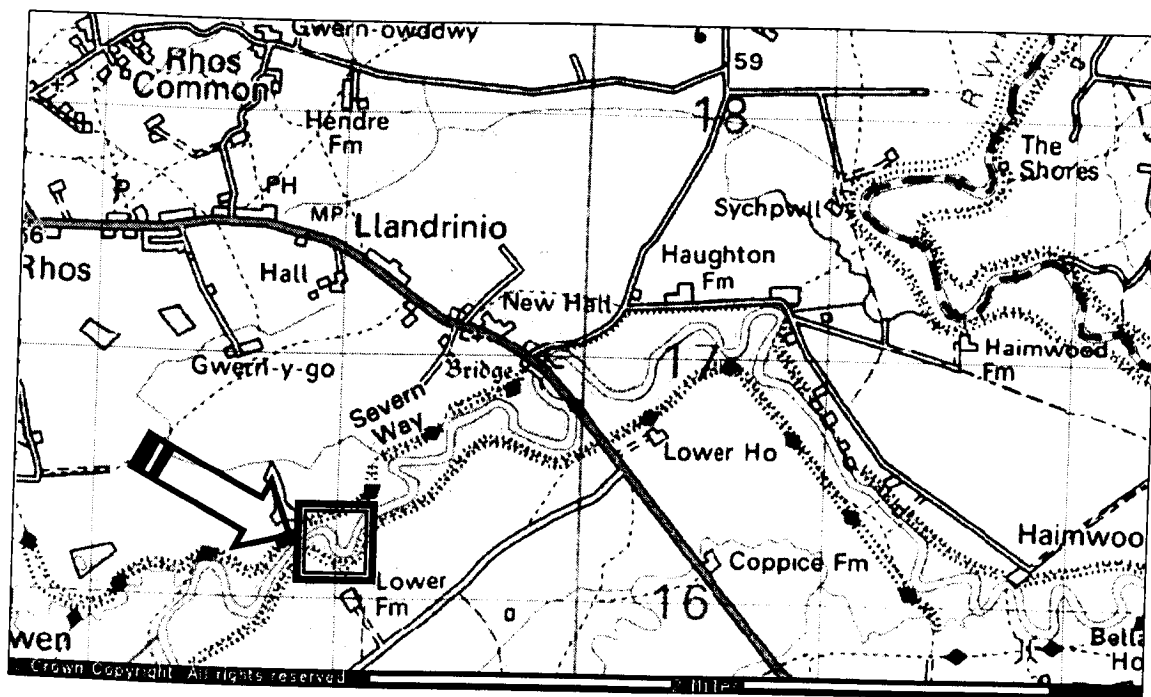
## **Application of CFD to Flooded Rivers**

### **– Rivers Severn and Ribble**

**Figures for Chapter 6**

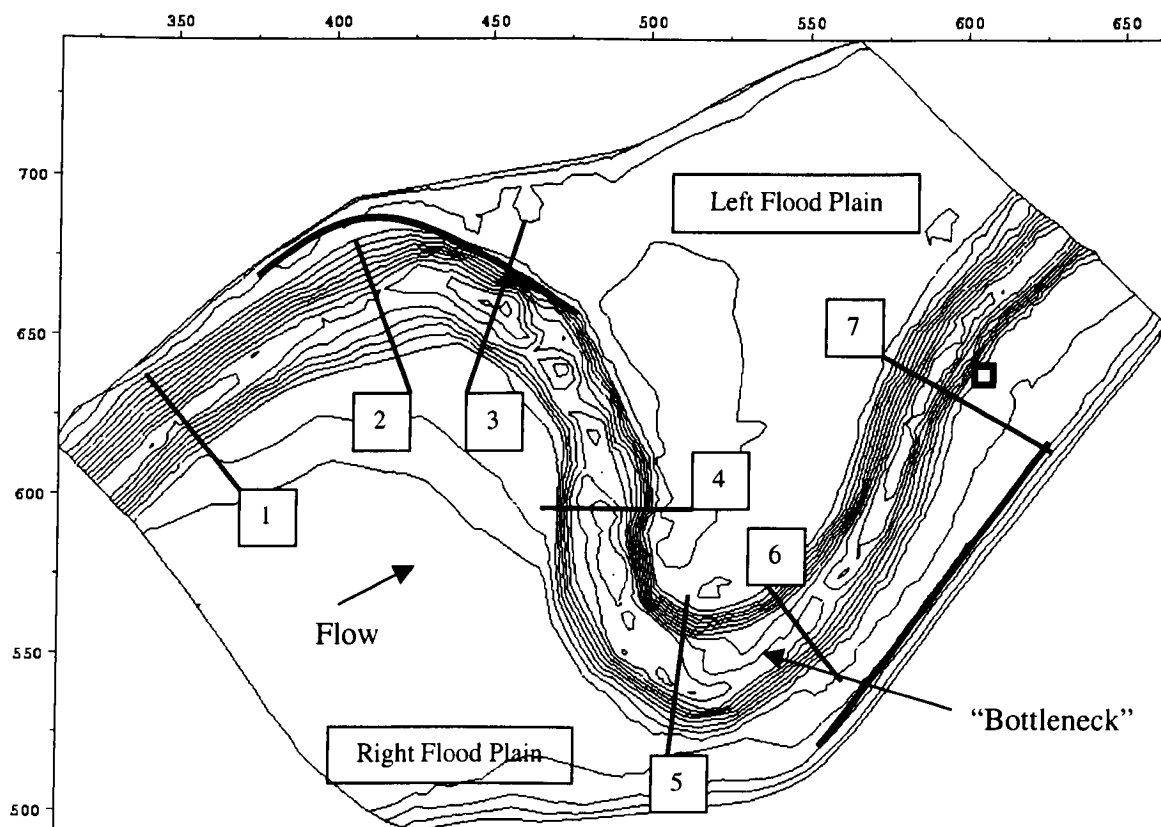


(a)

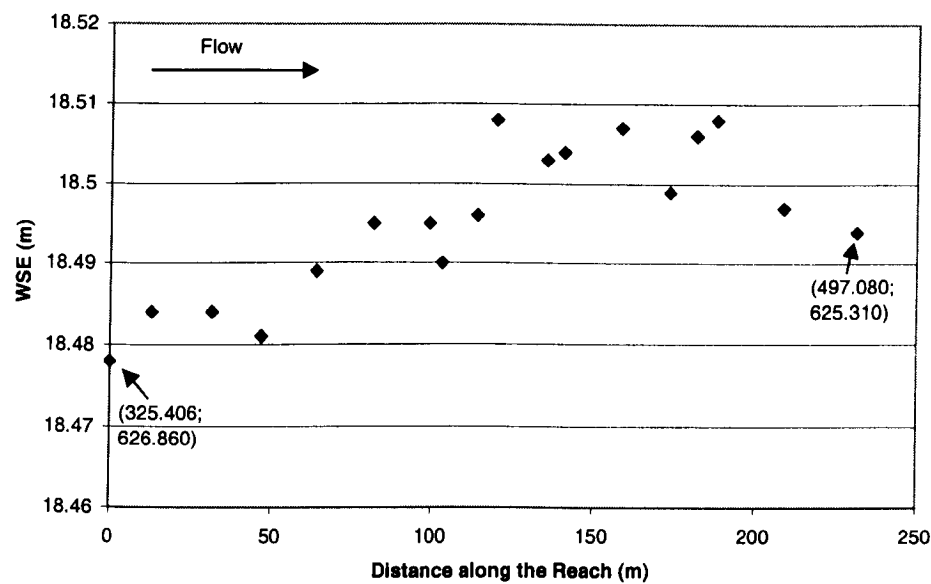


(b)

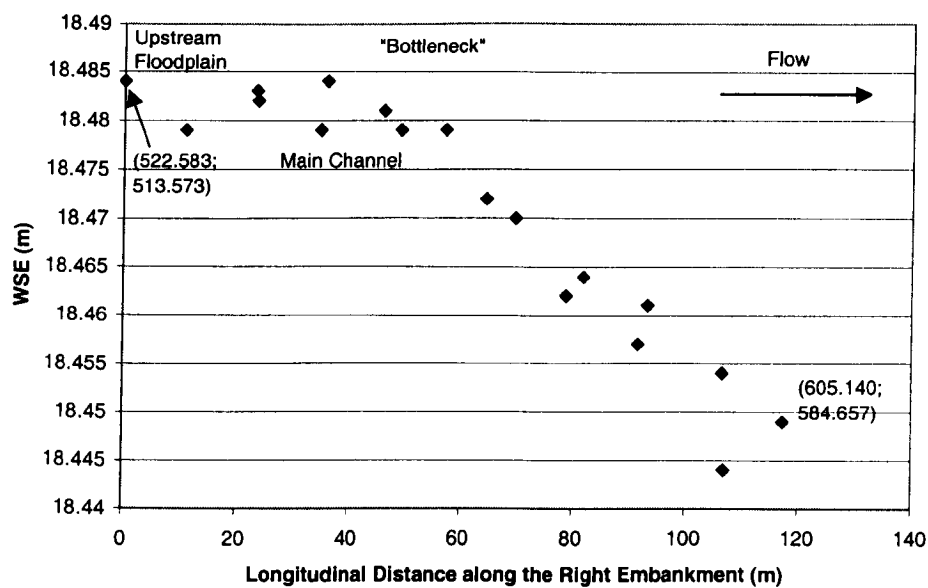
Fig. 6.1 – Location of the River Sever Site (MultiMap.Com)



**Fig. 6.2 – Plan View of the Severn, Location of the Cross-Sections, Path of the Free Surface Measurements — and Location of the Measurement Tower □**

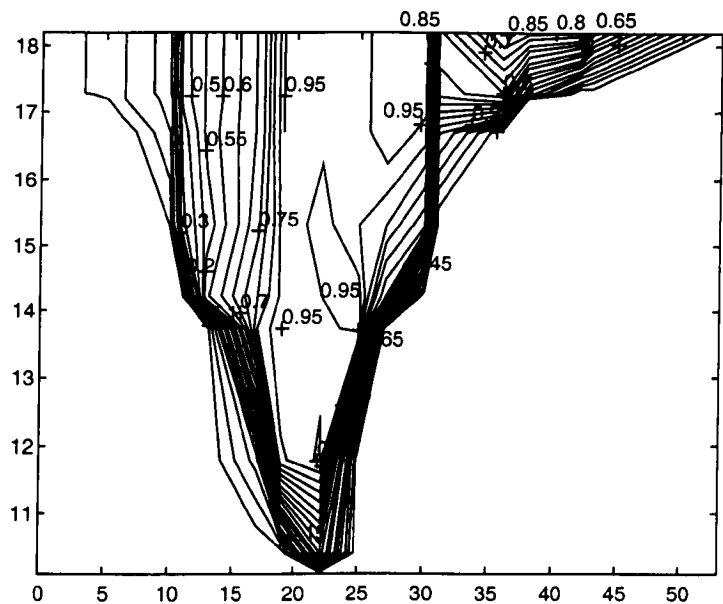


(a)

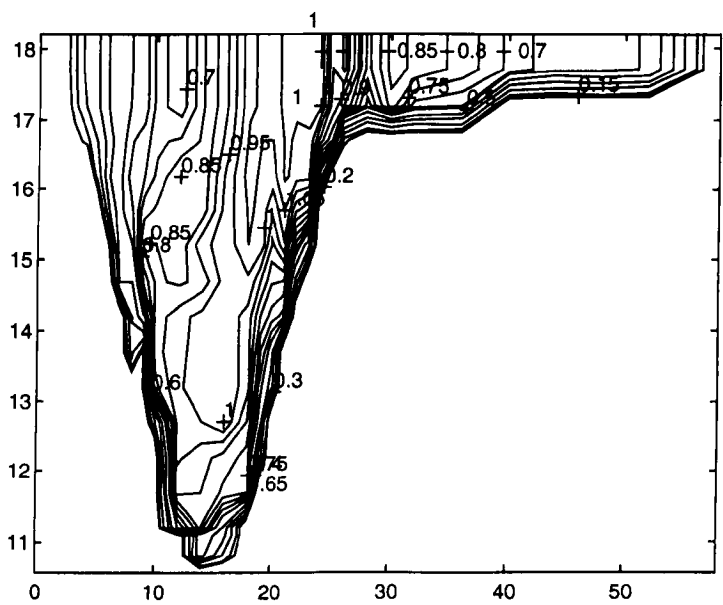


(b)

**Fig. 6.3 – Observed Water Surface Elevation for the Event of 14 December 1999:**  
**(a) Along the First Bend**  
**(b) Along the Right Bund**  
**(point planview coordinates in brackets)**

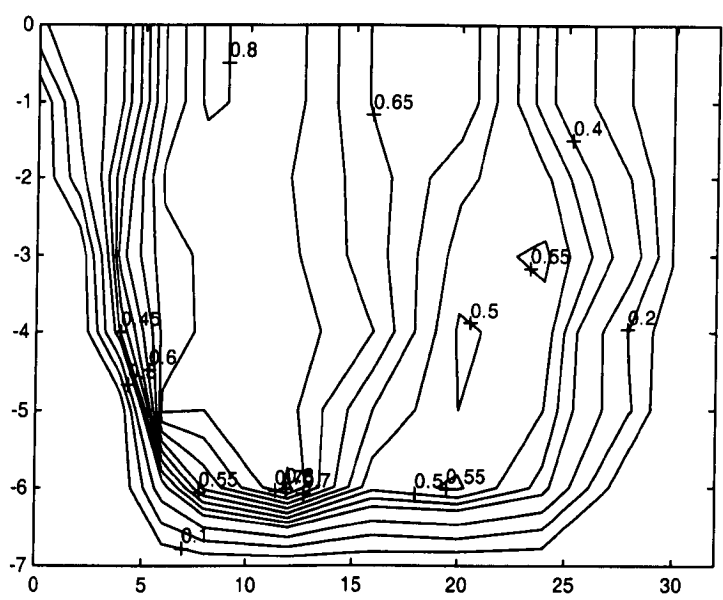


**Fig. 6.4 – Measured Velocity Profile at Cross-Section 7 in the Severn (m/s; December 1999)**

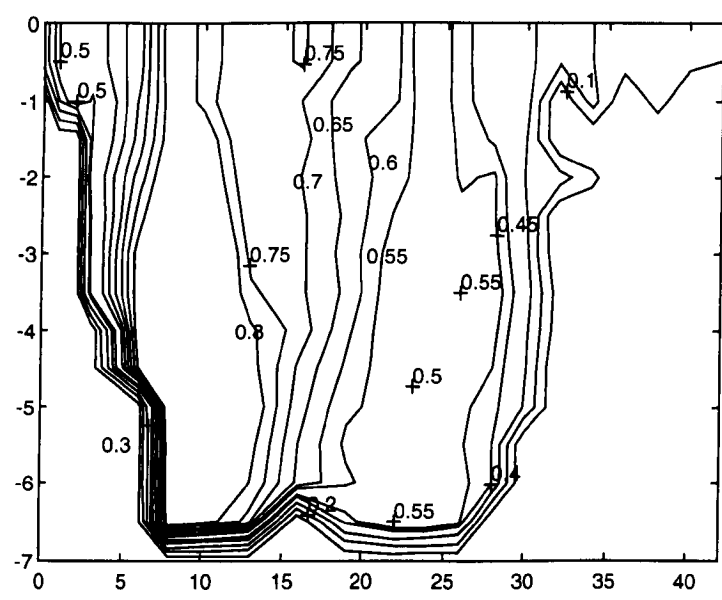


**Fig. 6.5 – Measured Velocity Profile at Cross-Section 7 in the Severn (m/s; March 2000)**

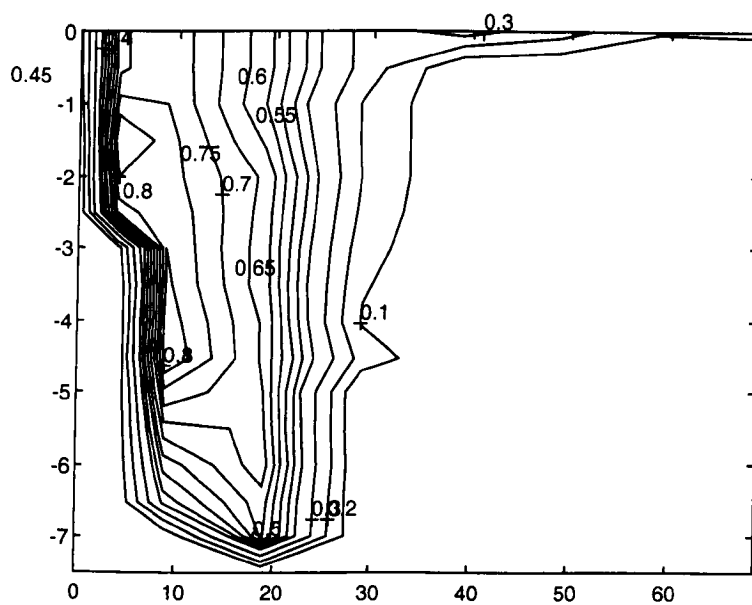




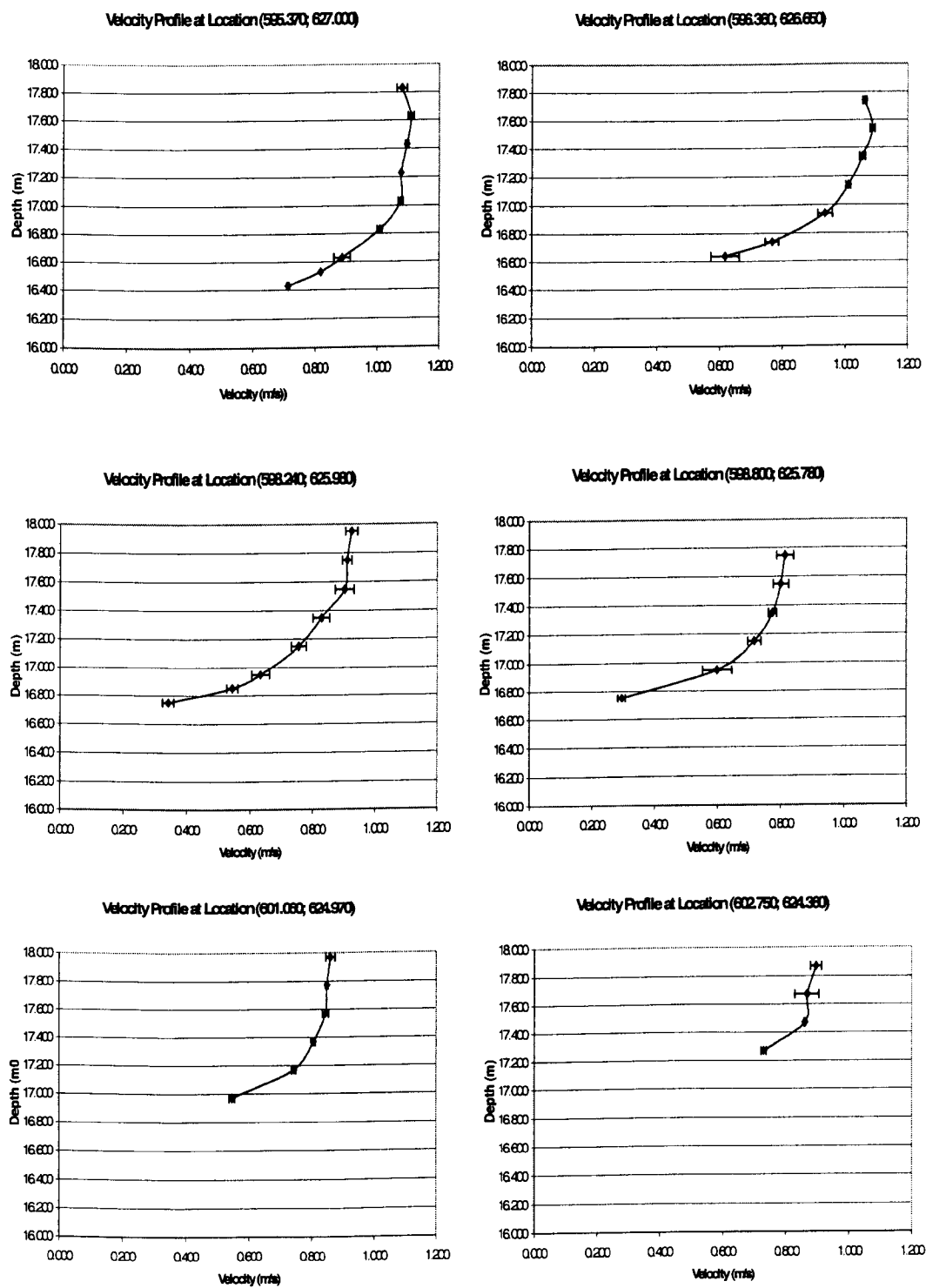
**Fig. 6.6 – Measured velocity Profile at Cross-Section 5 in the Severn (m/s; October 2000)**



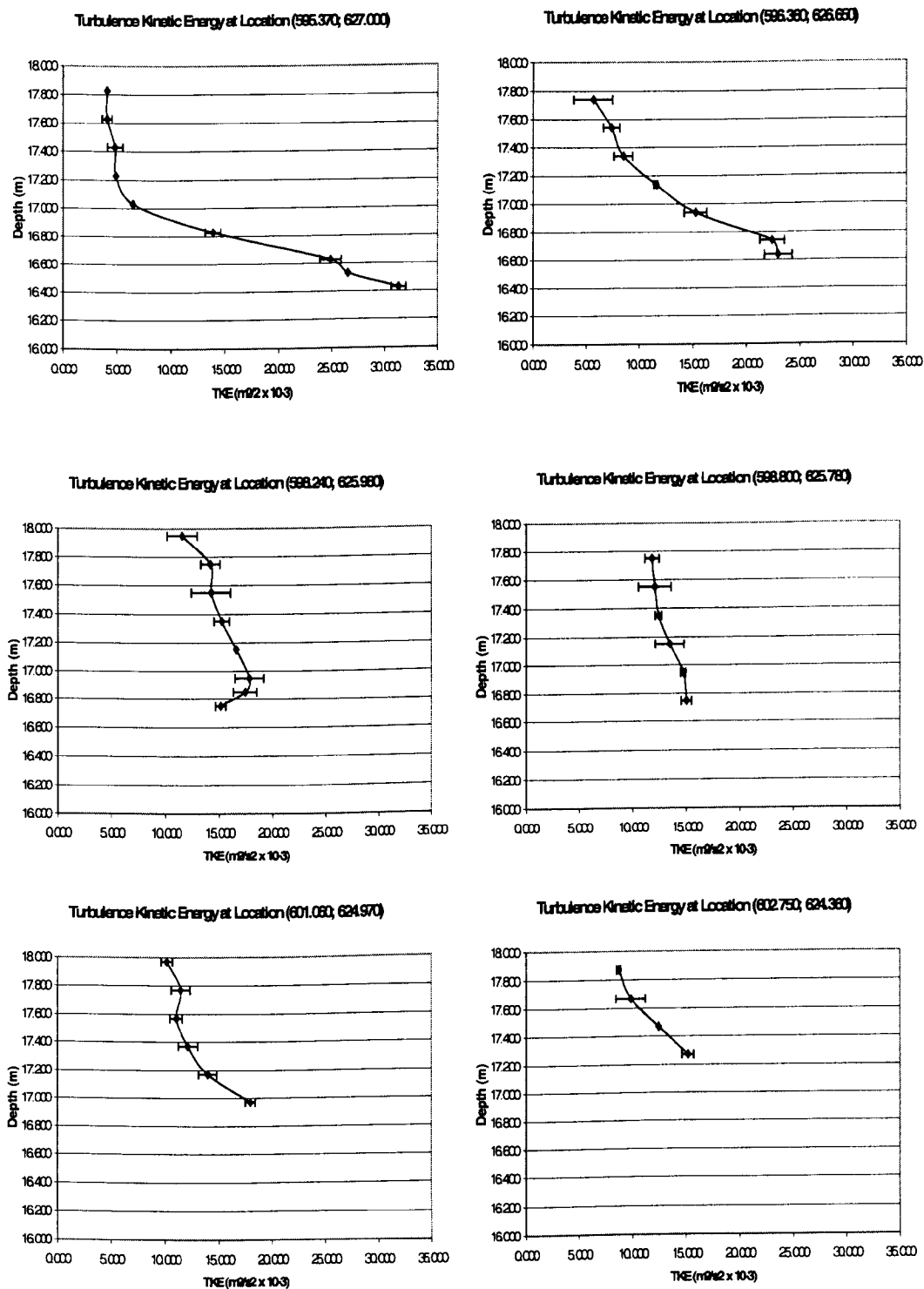
**Fig. 6.7 – Measured Velocity Profile at Cross-Section 5 in the Severn (m/s; November 2000)**



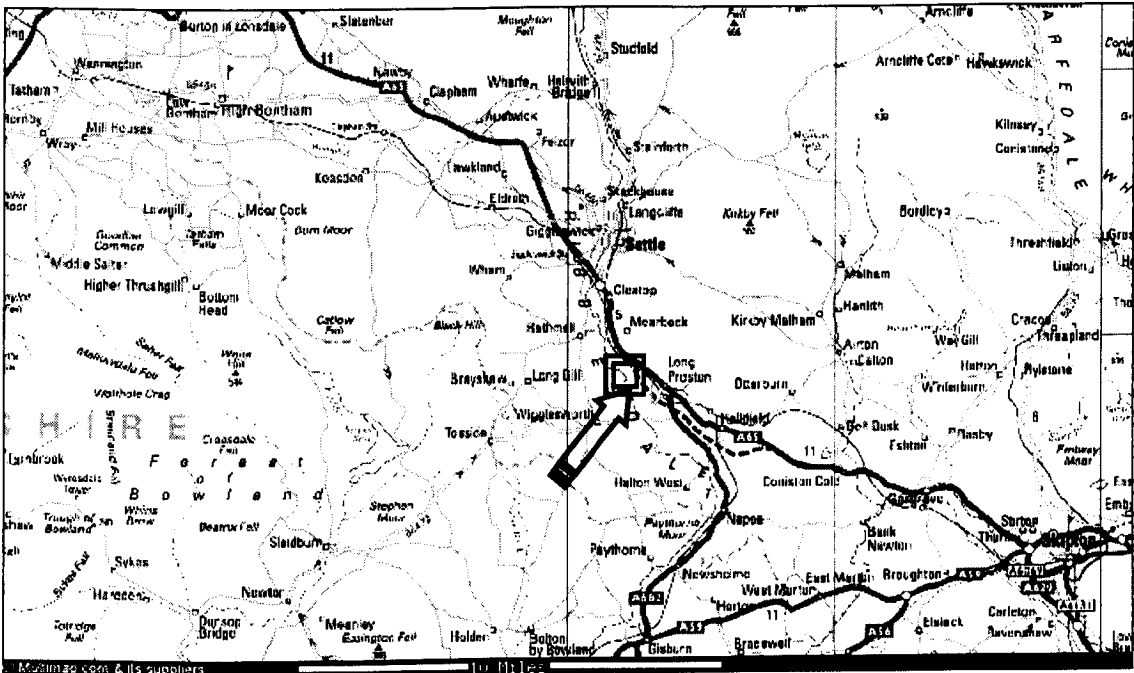
**Fig. 6.8 – Measured velocity Profile Between Cross-Sections 4 and 5 in the Severn (m/s; December 2000)**



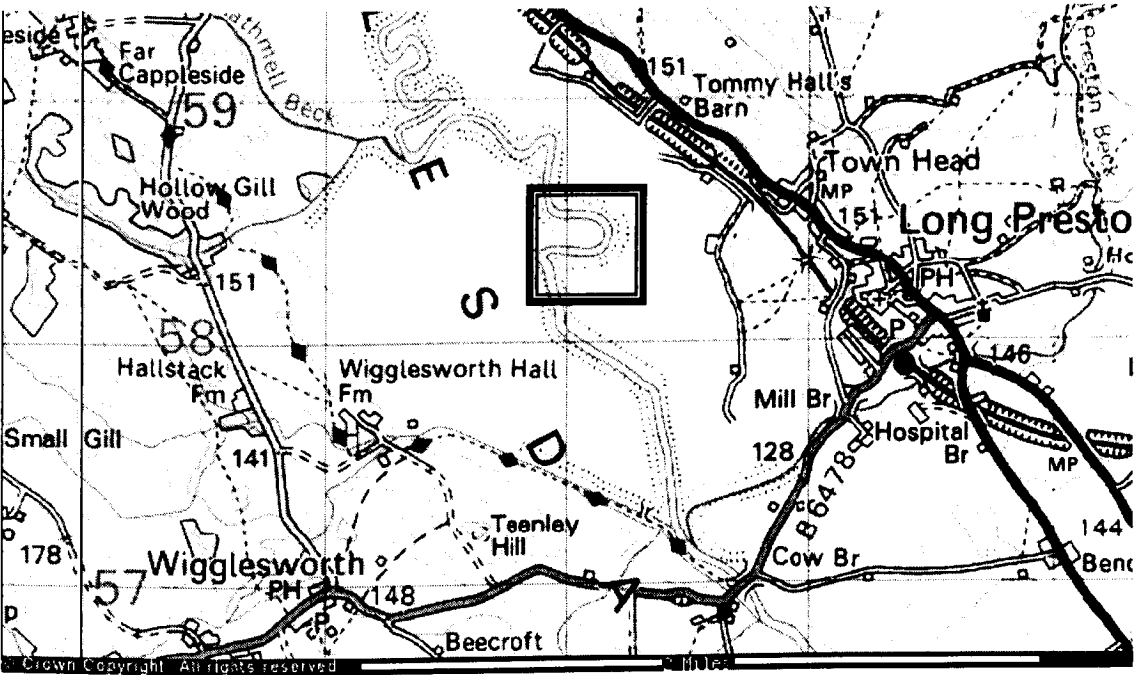
**Fig. 6.9 – Velocity Profiles along the Right Main Channel Bank of the River Sever at the Tower (m/s; March 2000)**



**Fig. 6.10 – Turbulence Kinetic Energy Profiles along the Right Main Channel Bank of the River Sever at the Tower ( $\text{m}^2/\text{s}^2$ ; March 2000)**

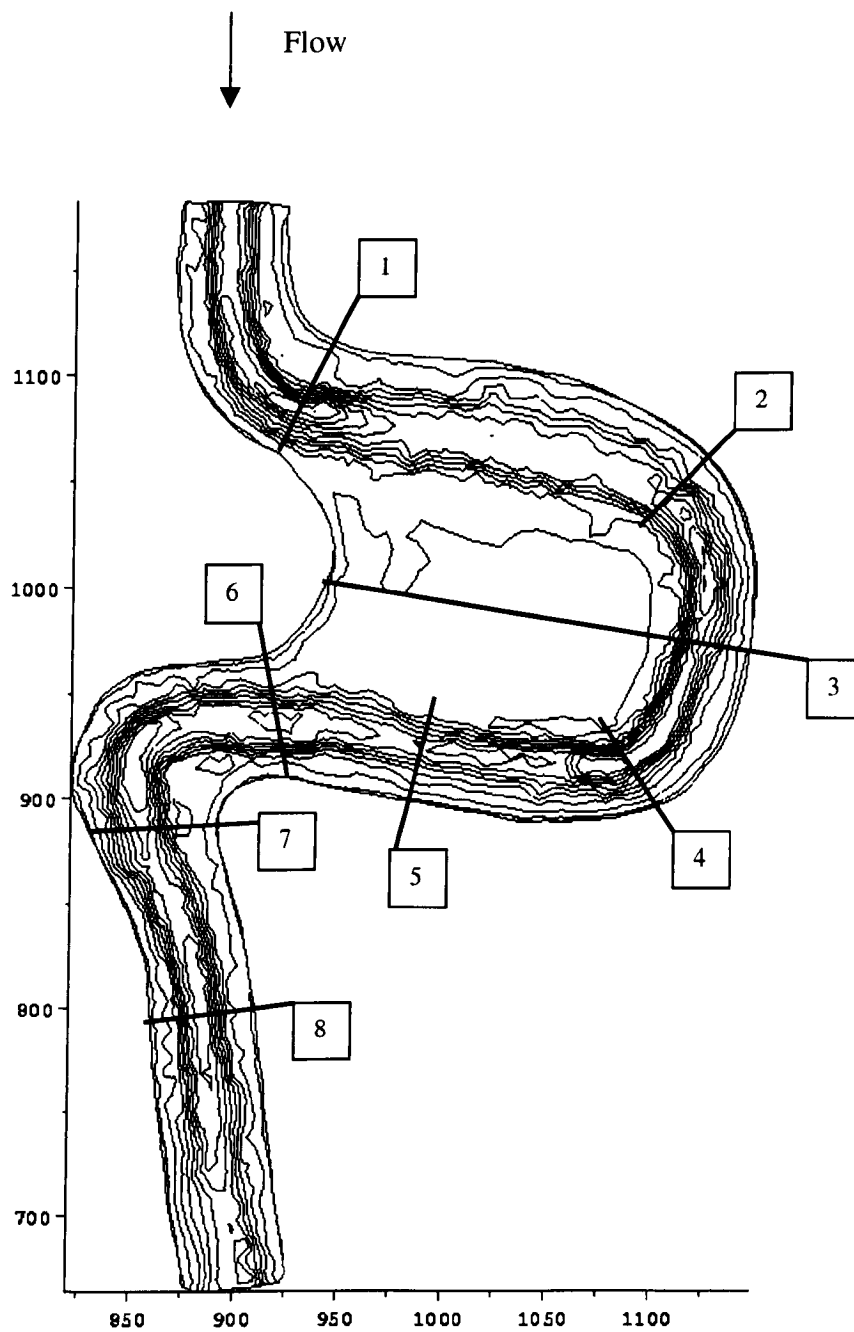


(a)

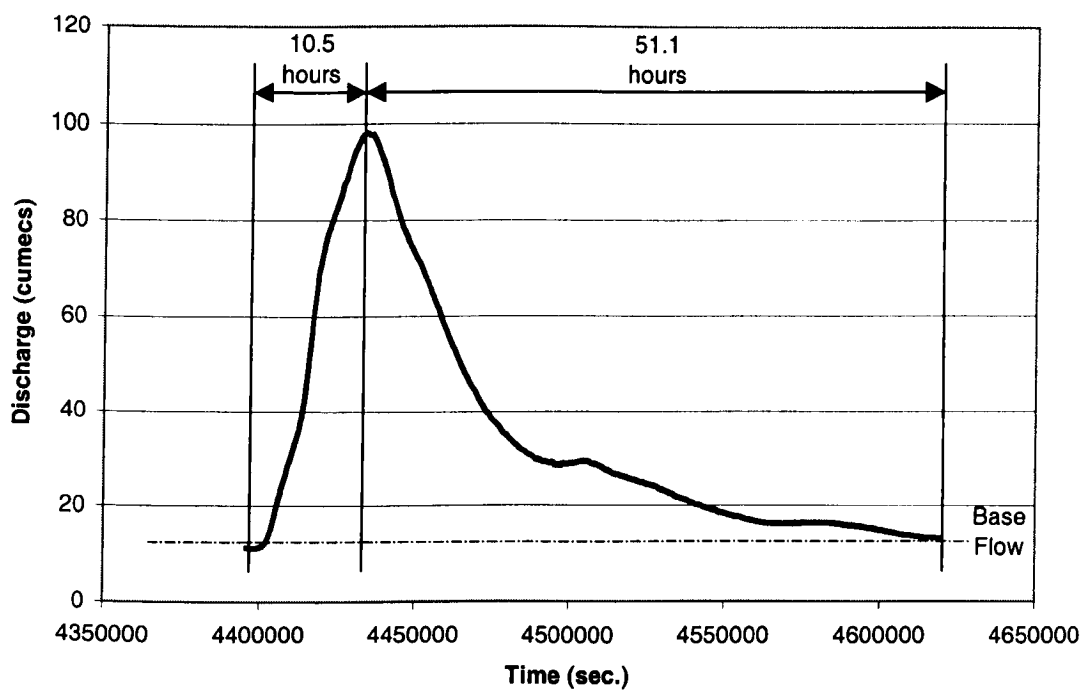


(b)

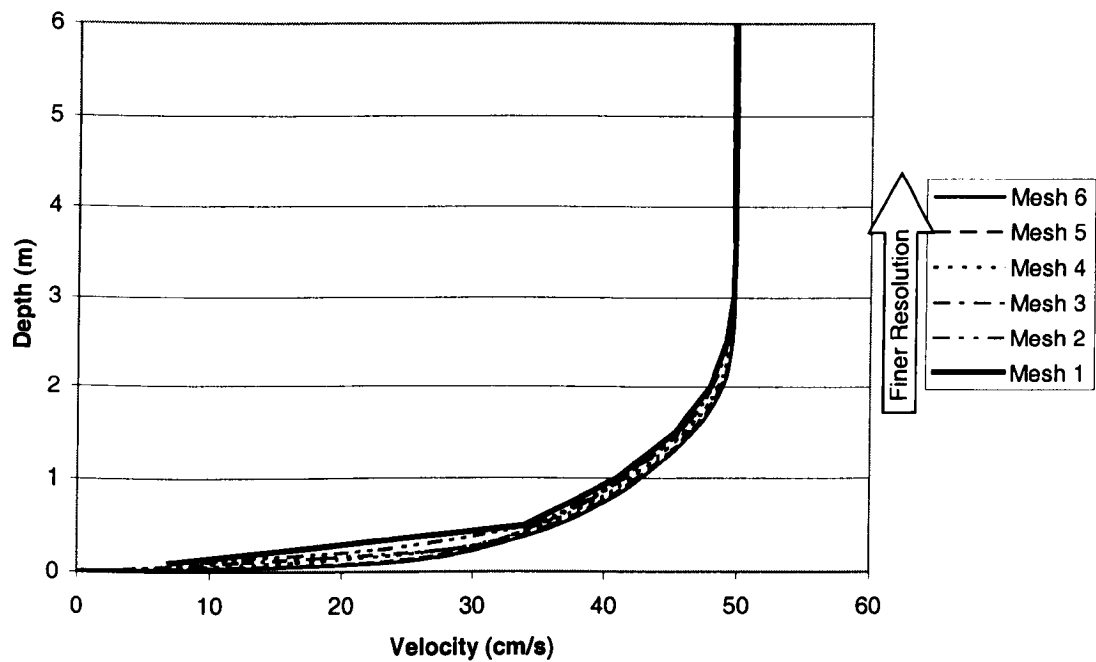
Fig. 6.11 – Location of the River Ribble Site (MultiMap.Com)



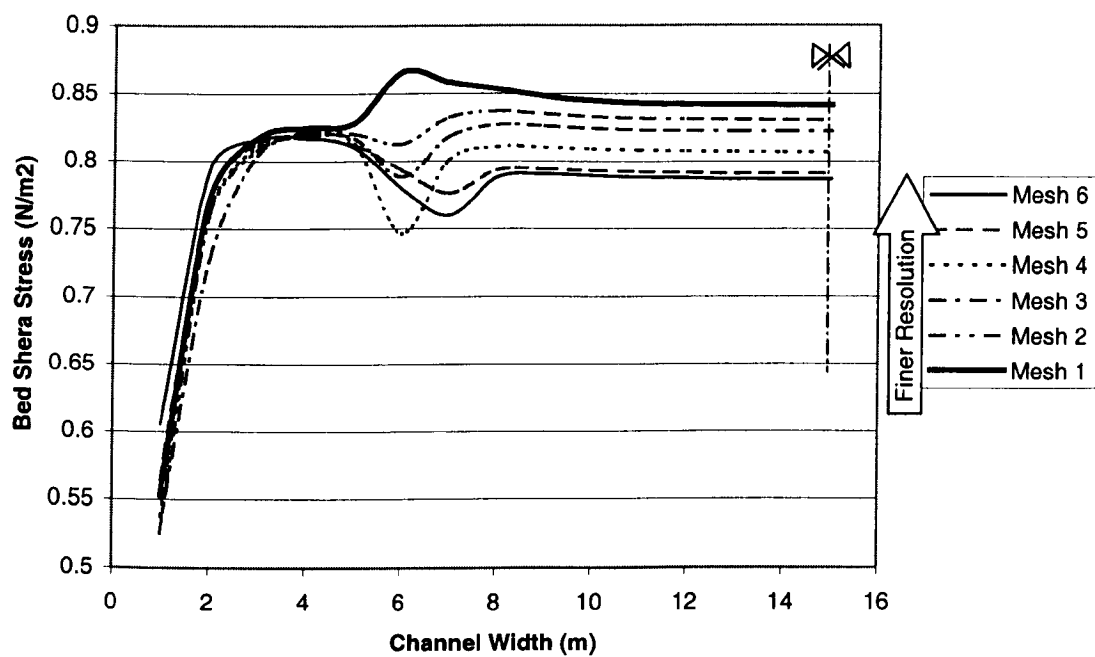
**Fig. 6.12 – Plan View of the Ribble and Location of Cross-Sections (Scale in m)**



**Fig. 6.13 – Peak Flood Hydrograph recorded by the Environmental Agency (EA) upstream of the River Ribble Study Reach over the Winter 1998-1999**

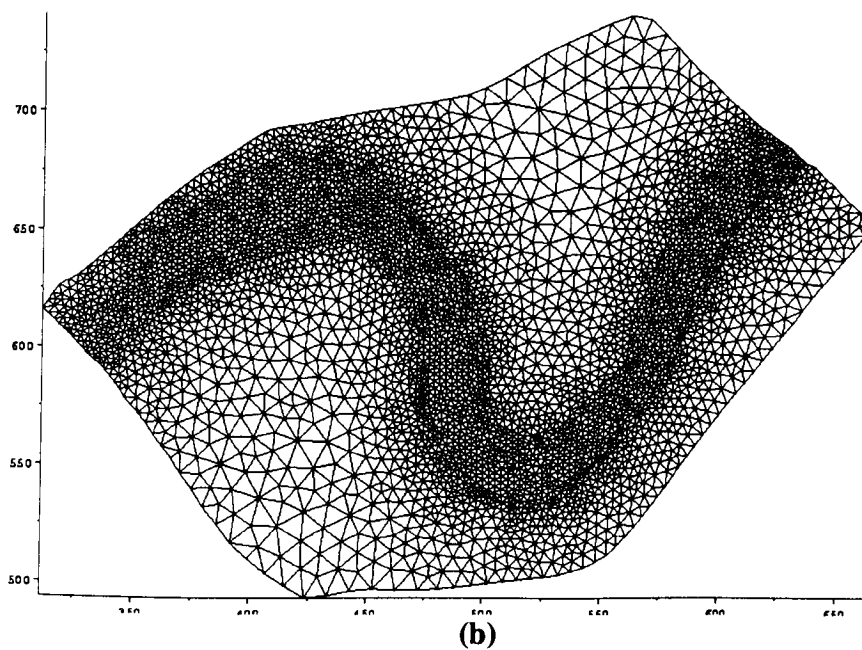
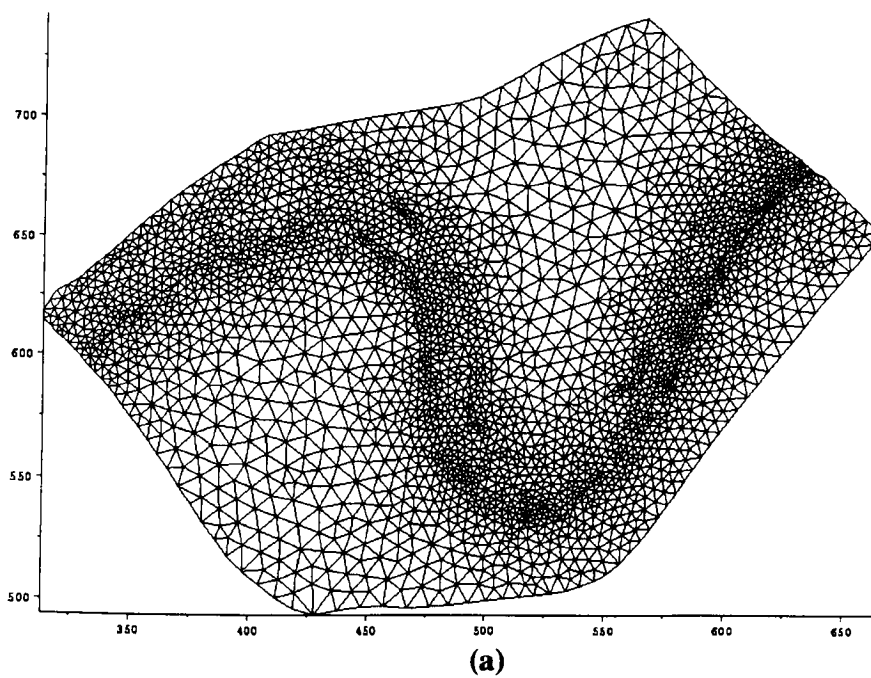


**Fig. 6.14 – Large-Scale Problem Grid Resolution: Impact on Velocity**



**Fig. 6.15 – Large-Scale Problem Grid Resolution: Impact on Bed Shear Stress**

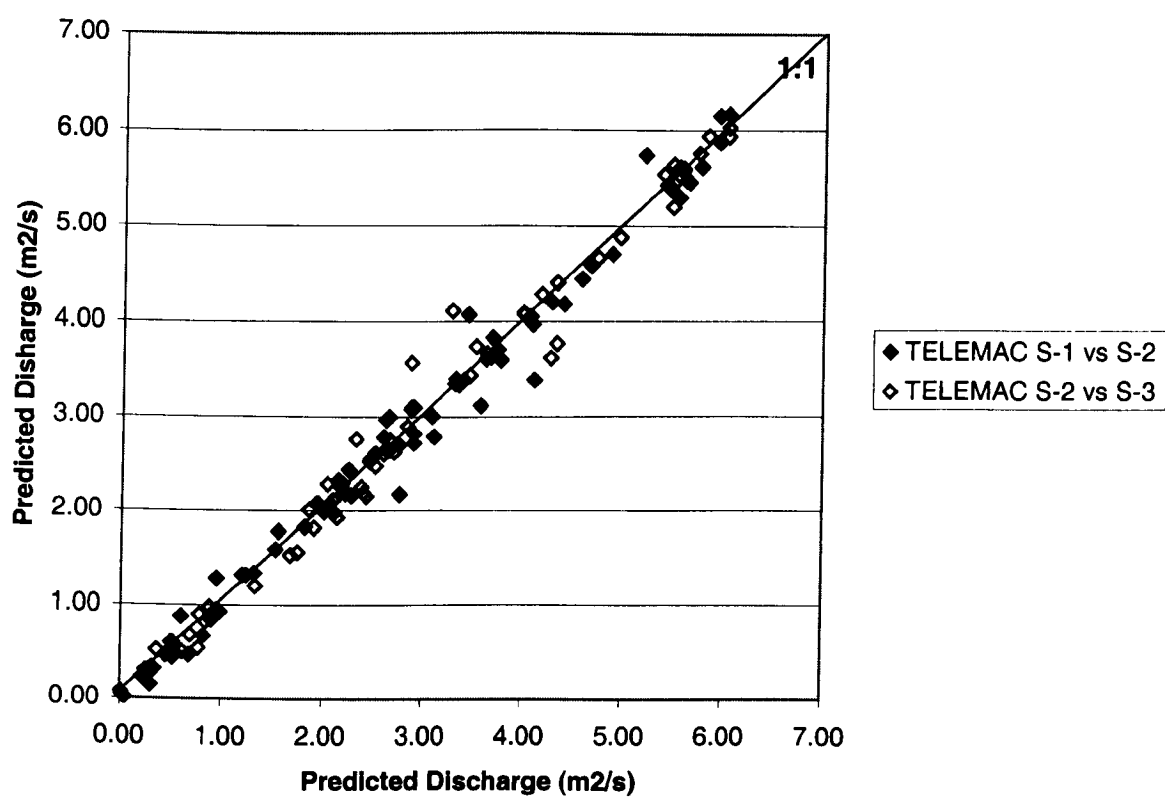




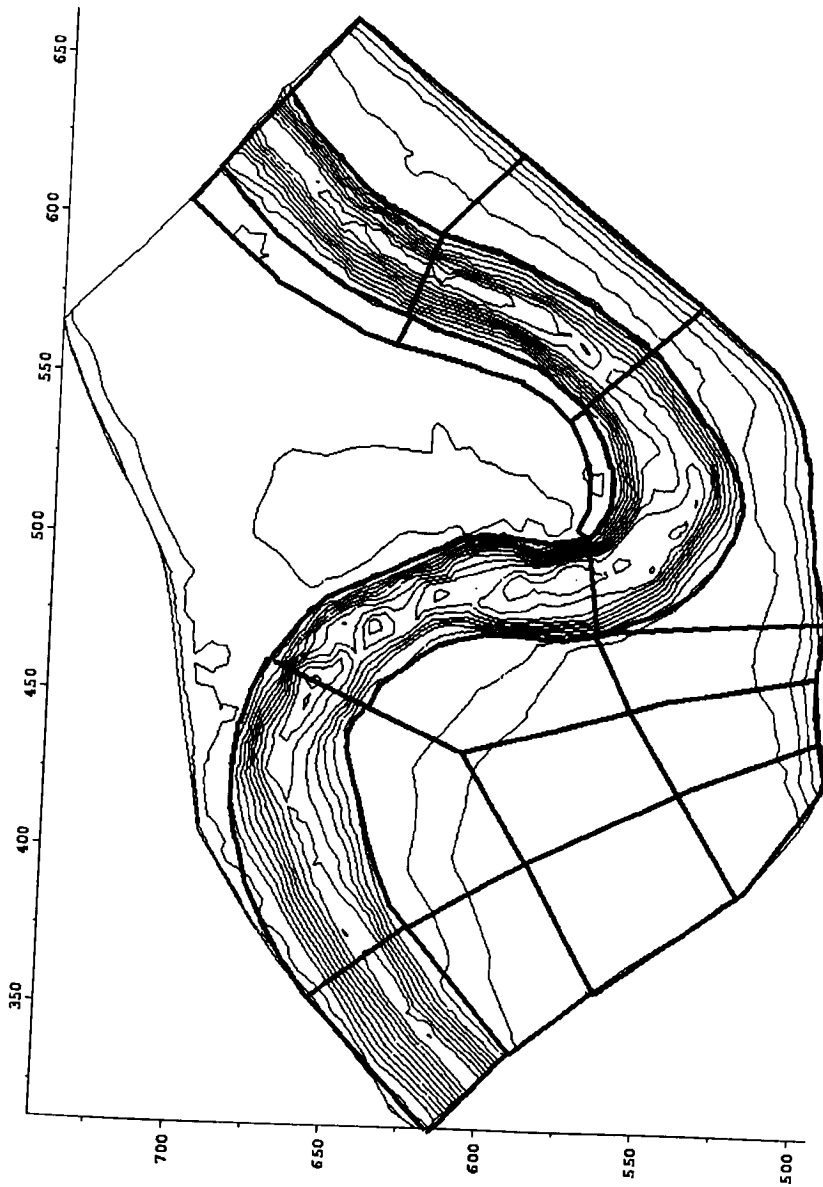
**Fig. 6.16 – Plan View Meshes for TELEMAC Models of the Severn:**

**(a) Mesh TELEMAC S-1**

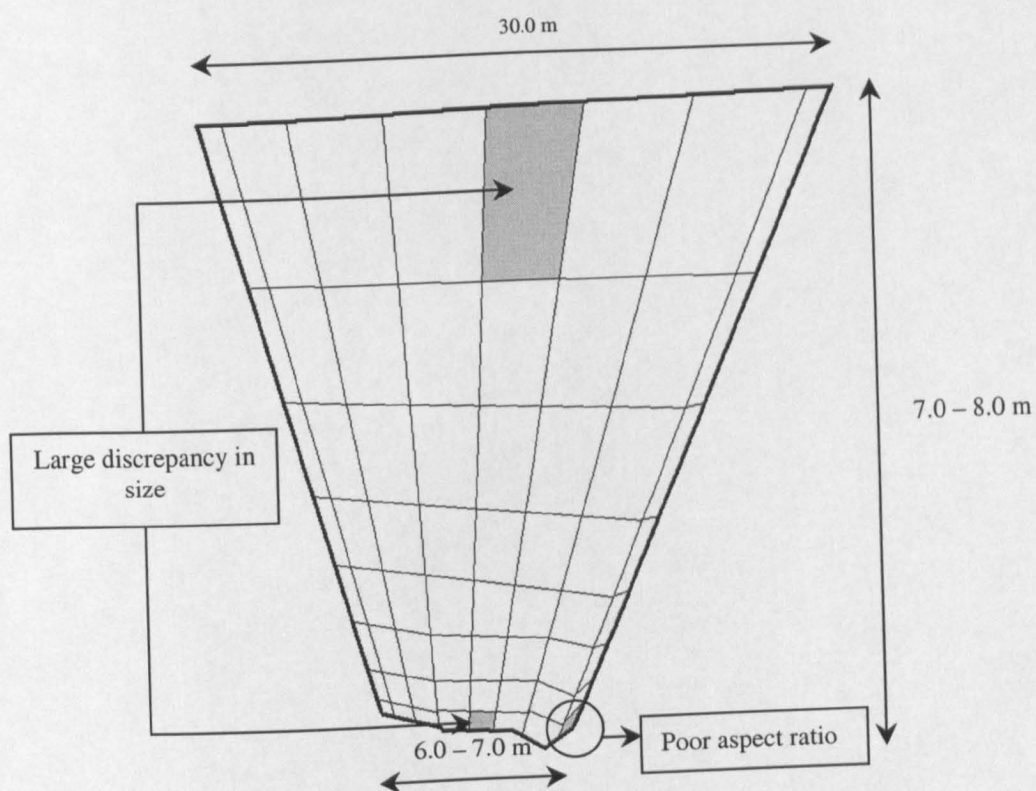
**(b) Mesh TELEMAC S-2**



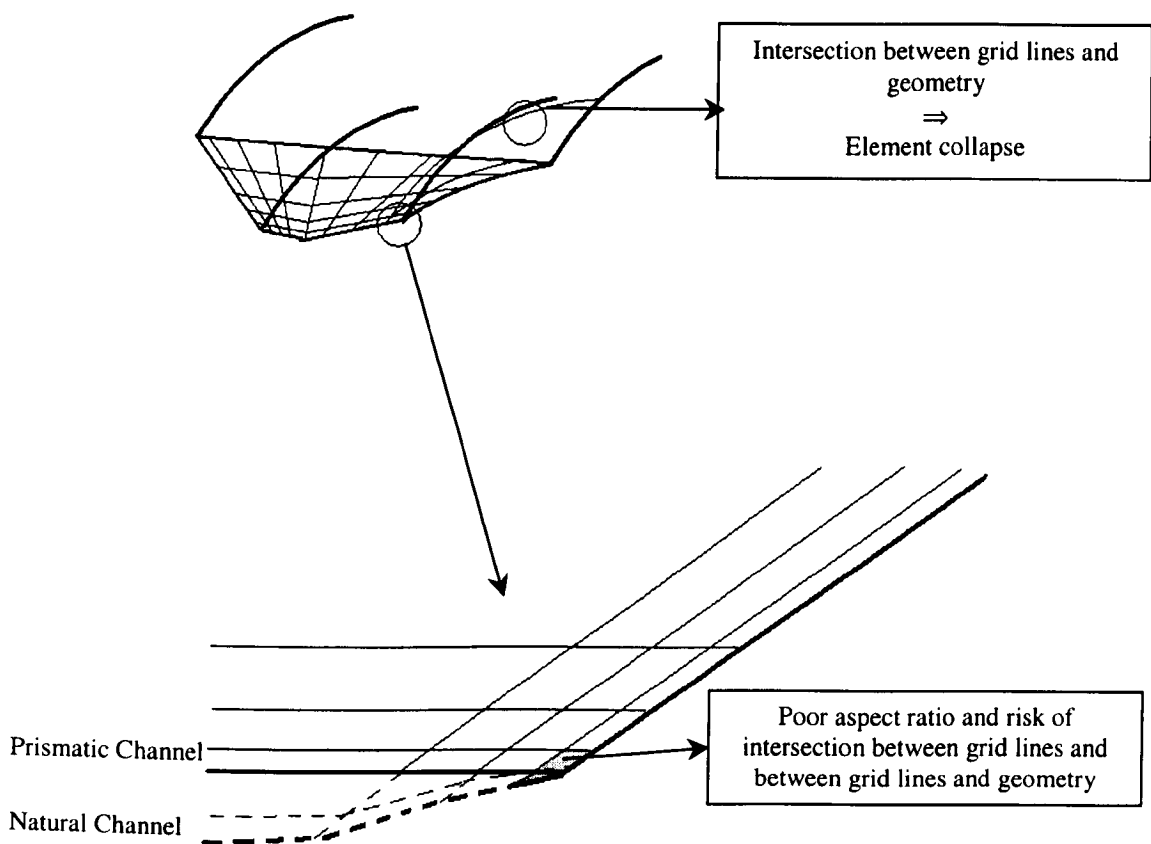
**Fig. 6.17 – Mesh Independence for River Severn Models using TELEMAC:  
Comparison of Calculated Fields at Sections 4, 5, 6 and 7 as well as on the  
Floodplain and along the Thalweg**



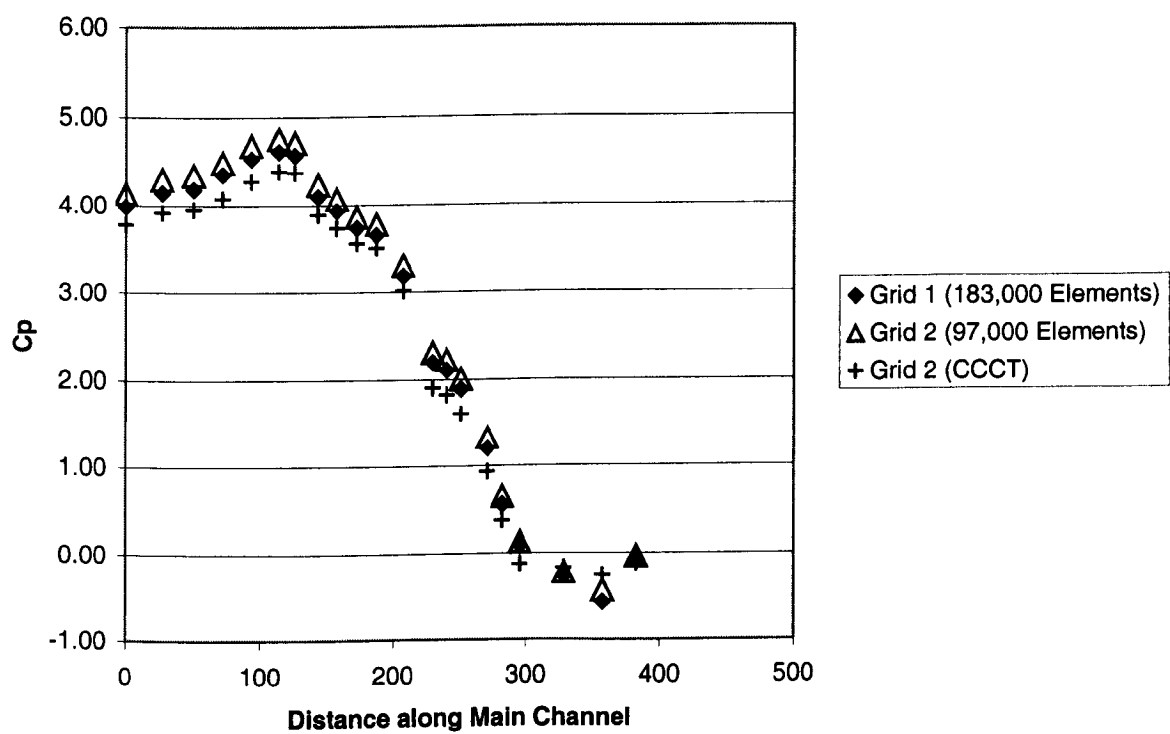
**Fig. 6.18 – River Severn Multi-Block Layout in CFX**



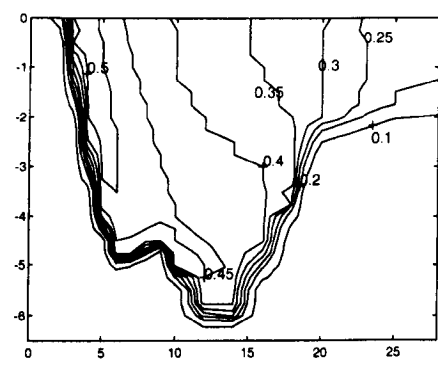
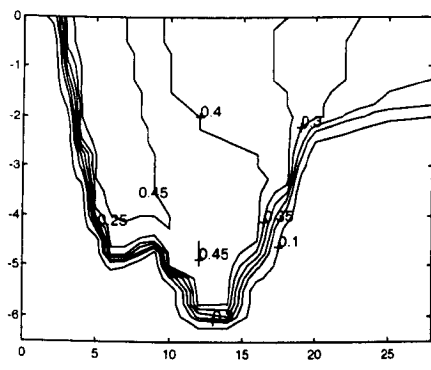
**Fig. 6.19 – CFX Main Grid Constraints in the Severn**



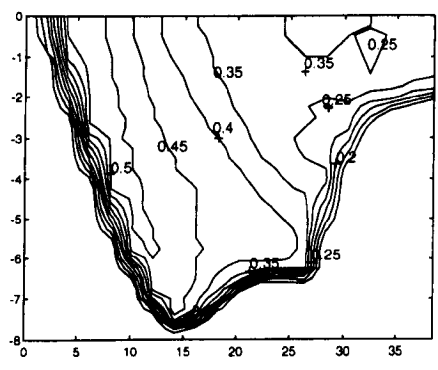
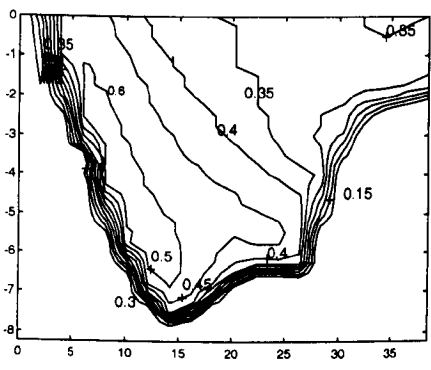
**Fig. 6.20 – CFX Main Grid Constraints in the Ribble**



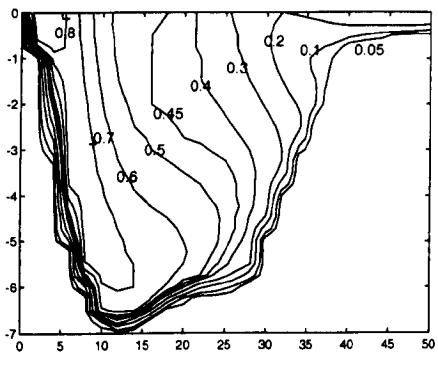
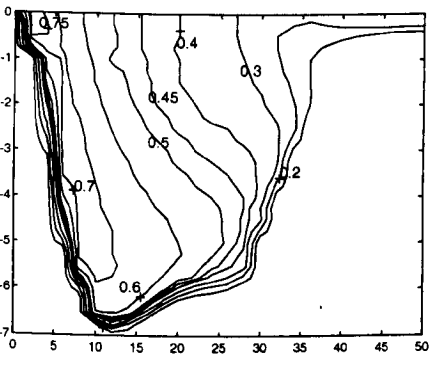
**Fig. 6.21 – Mesh Independence Test for River Severn Model using CFX:  
Comparison of Non-dimensional Pressure along the Main Channel, at the Bed**



Cross-Section 3

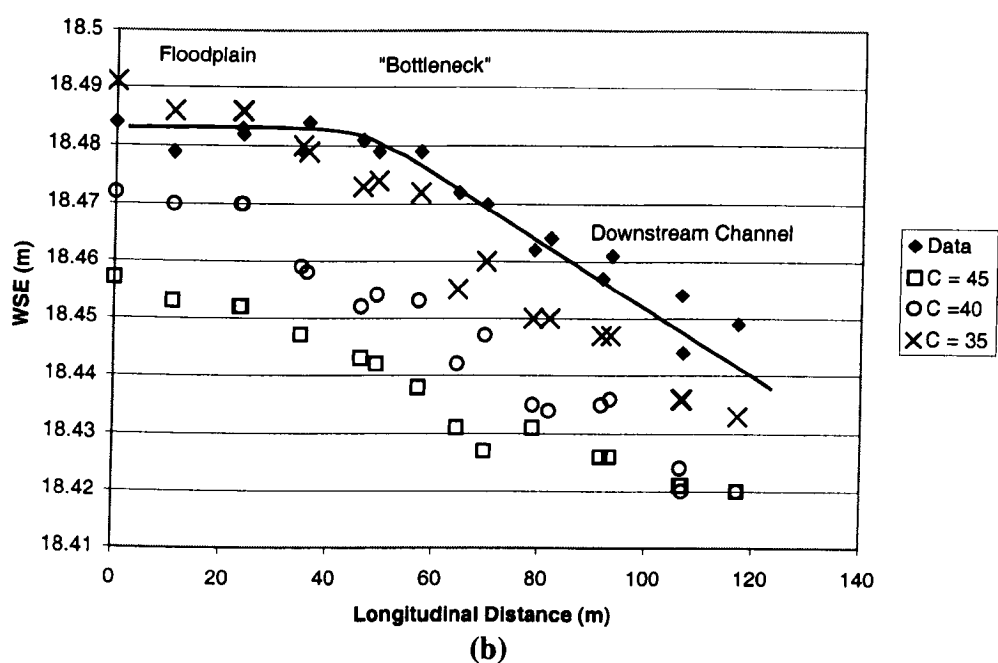
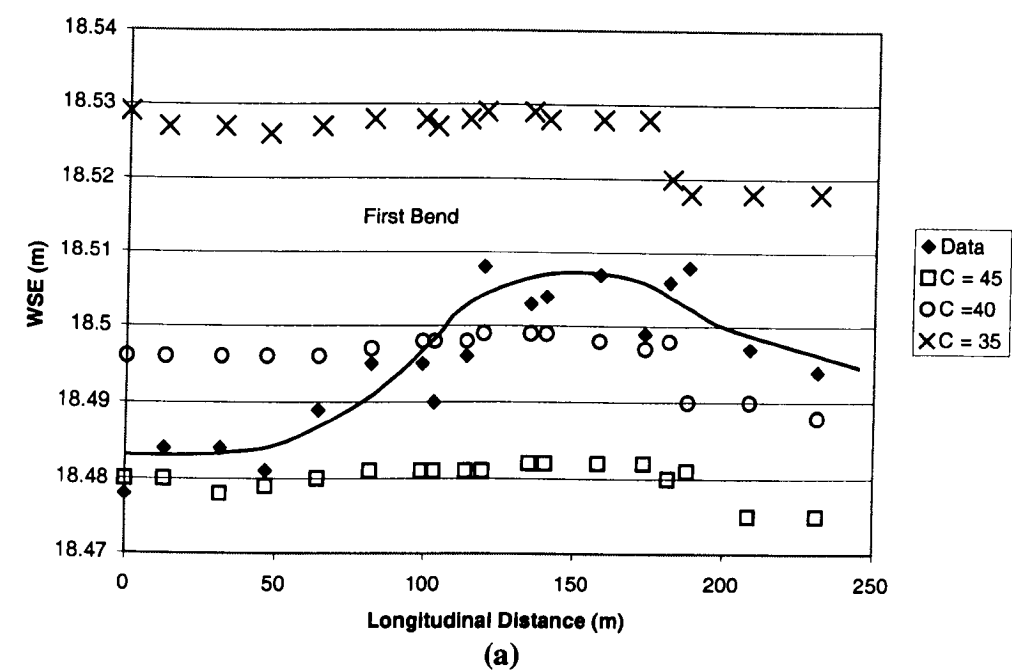


Cross-Section 4



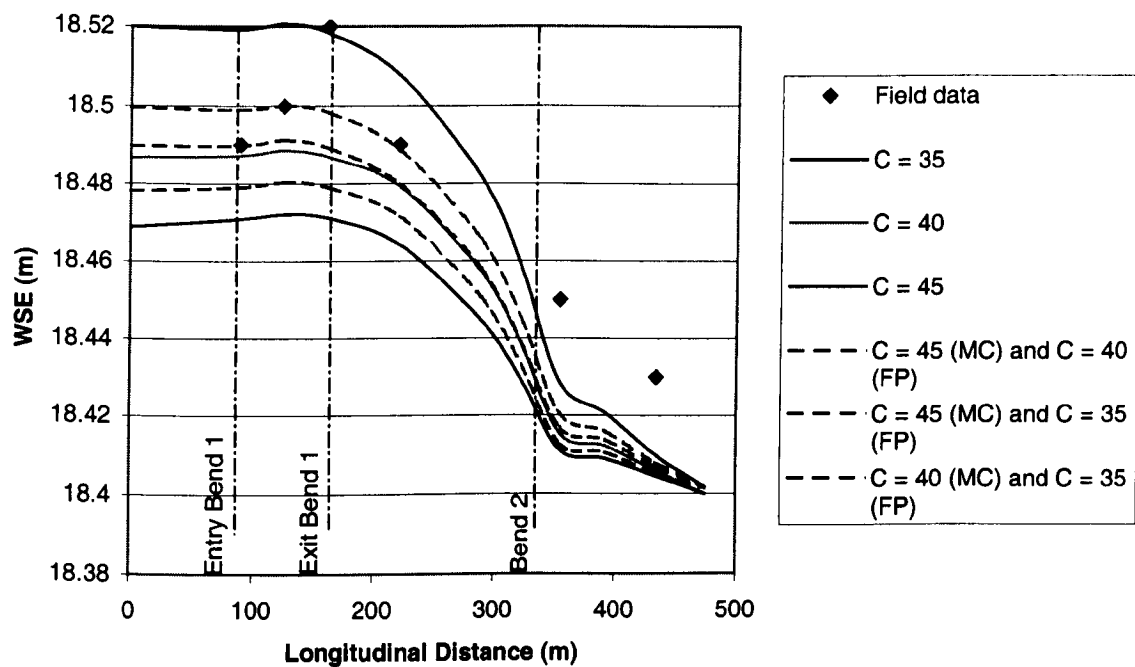
Cross-Section 5

**Fig. 6.22 – Comparison between the Results with Hybrid (left) and QUICK-CCCT (right) at Cross-Sections 3, 4 and 5 for the River Severn CFX Model**

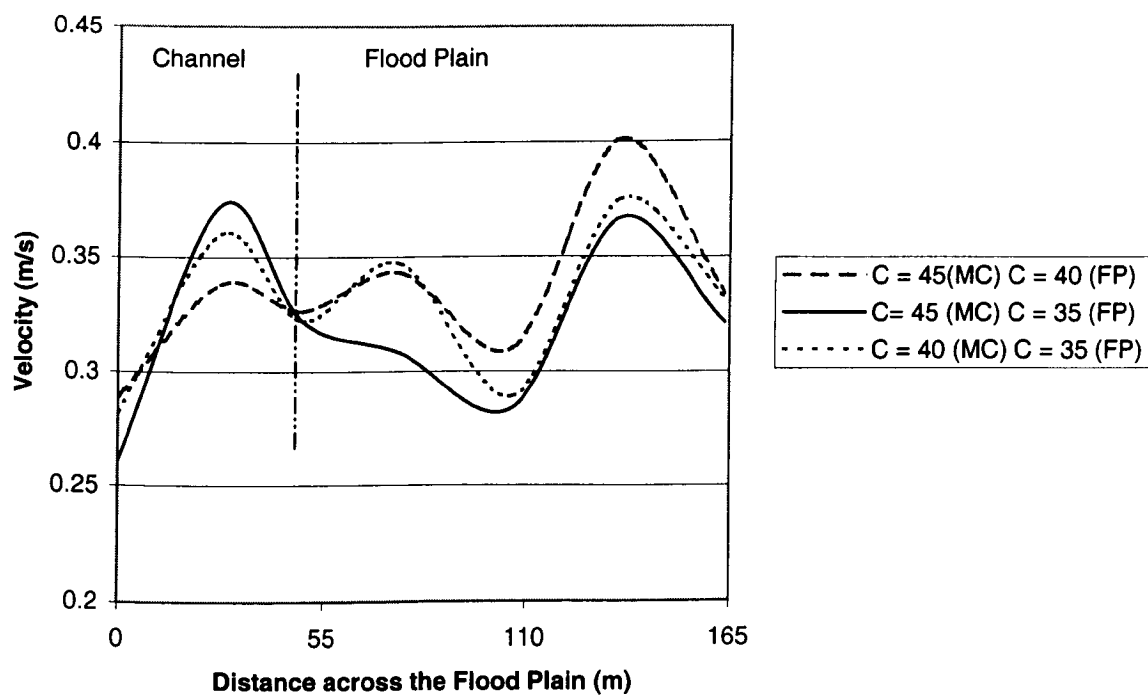


**Fig. 6.23 – Comparison of Water Surface Elevations between TELEMAC Models and Field Data (100 m<sup>3</sup>/s Event of Dec. 1999):**  
**(a) along the upstream first bend**  
**(b) along the right embankment**

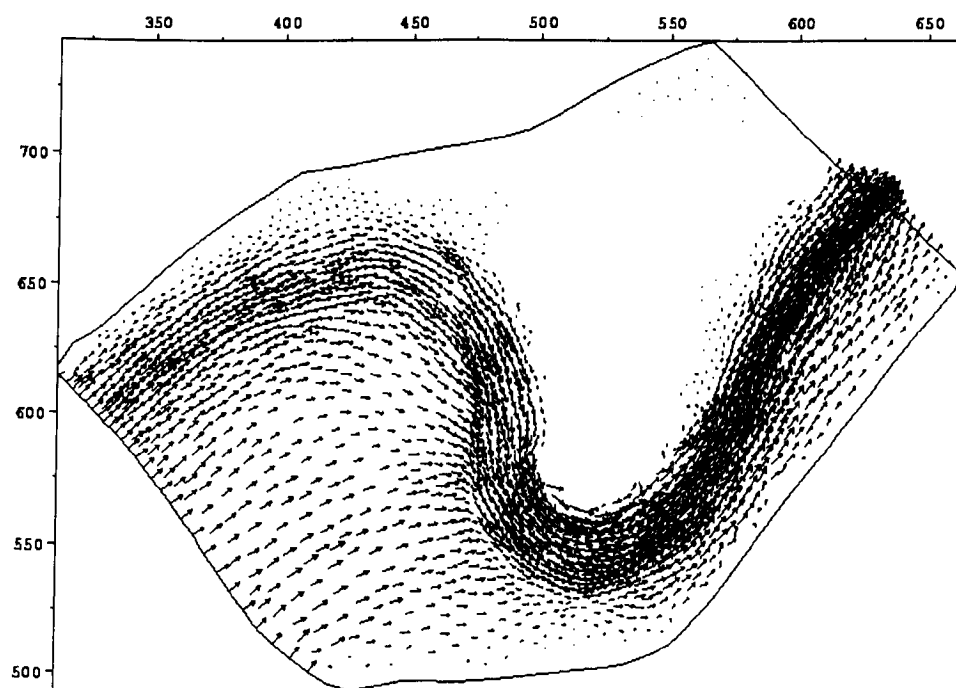




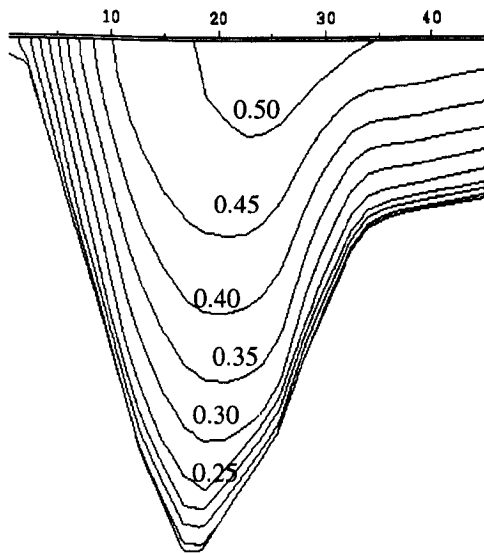
**Fig. 6.24 – TELEMAC Model of the Severn: Sensitivity Analysis of the Free Surface to Roughness**



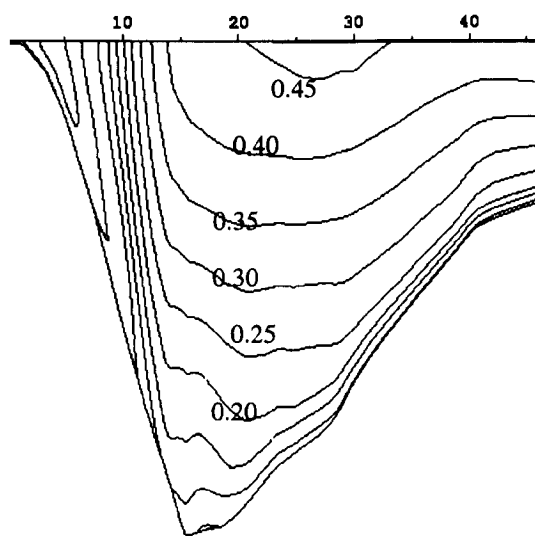
**Fig. 6.25 – TELEMAC Model of the Severn: Impact of Roughness on Velocity Distribution across the Upstream Part of the Reach**



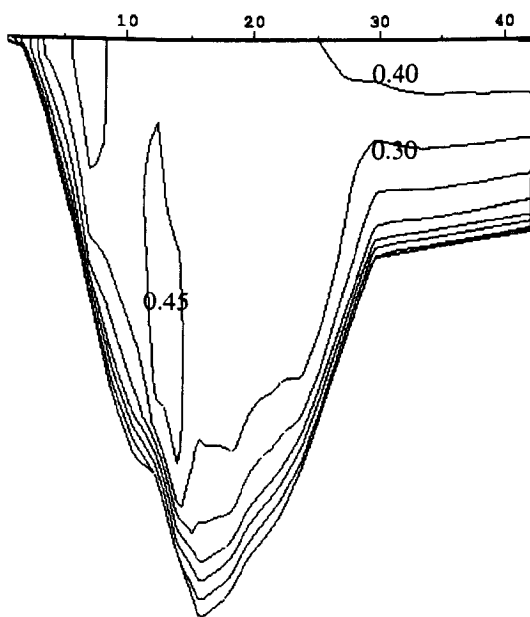
**Fig. 6.26 – River Severn TELEMAC Depth-Averaged Velocity Vectors  
for a Flow of  $100 \text{ m}^3/\text{s}$**



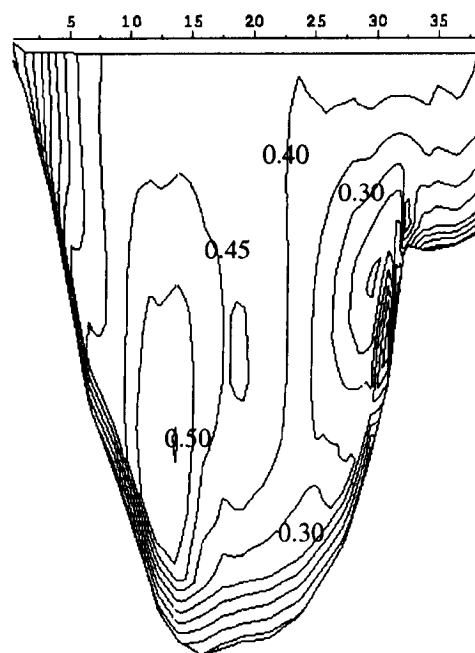
Cross-Section 1



Cross-Section 2

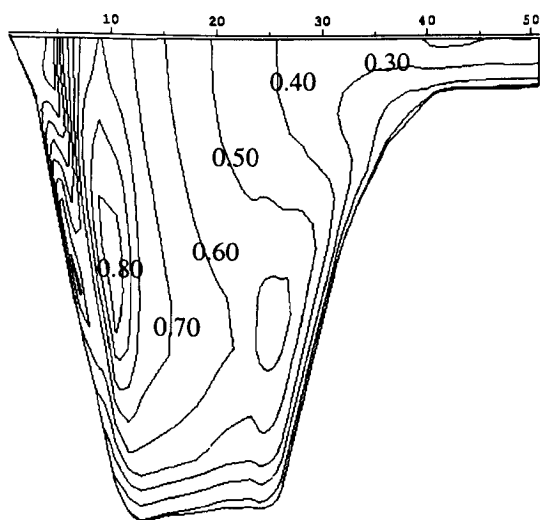


Cross-Section 3

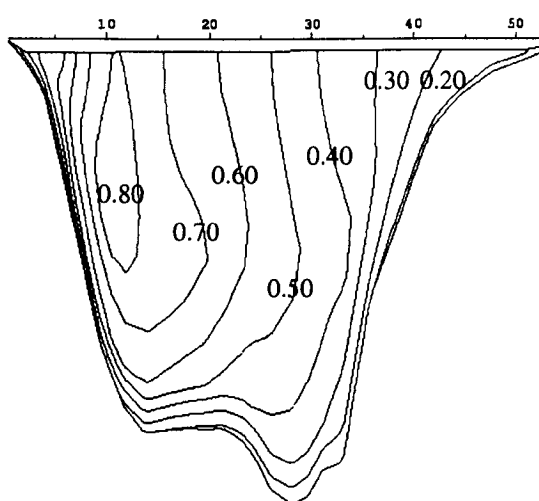


Cross-Section 4

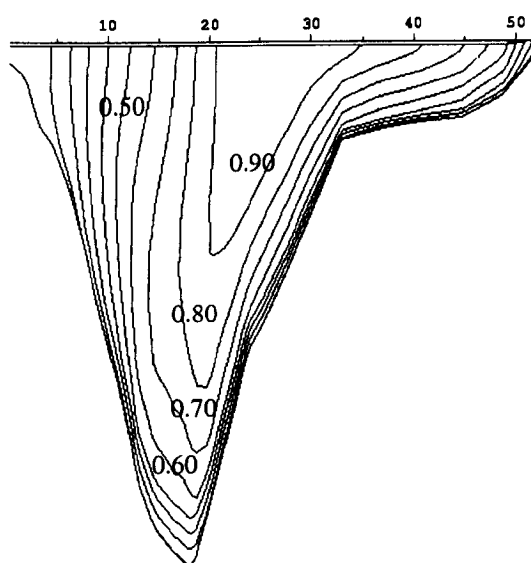
**Fig. 6.27 – River Severn TELEMAC Velocity Profile (m/s) at Cross-Sections 1, 2, 3 and 4 ( $C = 45 \text{ m}^{1/2}/\text{s}$  (MC) and  $35 \text{ m}^{1/2}/\text{s}$  (FP); Mesh S-2; Mixing-Length Model)**



Cross-Section 5

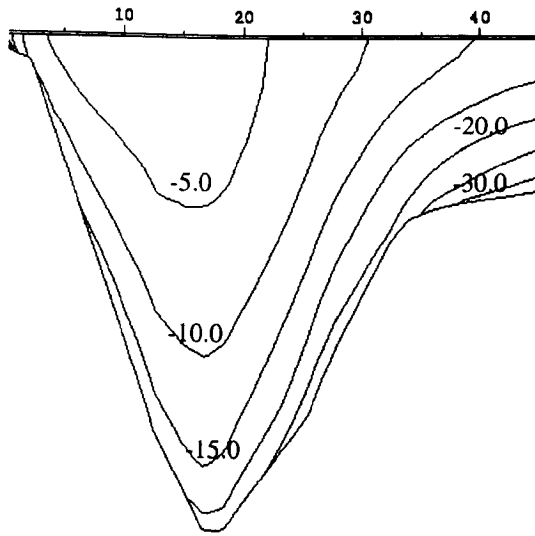


Cross-Section 6

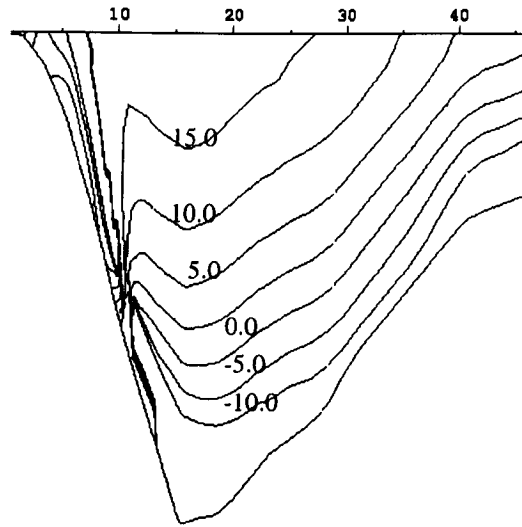


Cross-Section 7

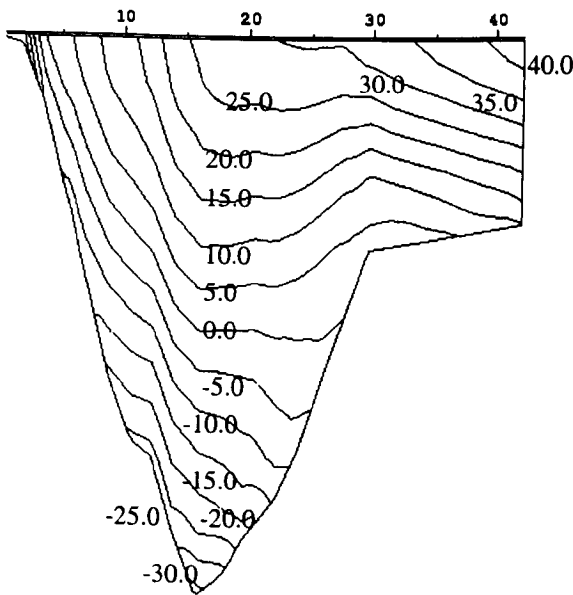
**Fig. 6.28 – River Severn TELEMAC Velocity Profile (m/s) at Cross-Sections 5, 6, and 7 ( $C = 45 \text{ m}^{1/2}/\text{s}$  (MC) and  $35 \text{ m}^{1/2}/\text{s}$  (FP); Mesh S-2; Mixing-Length Model)**



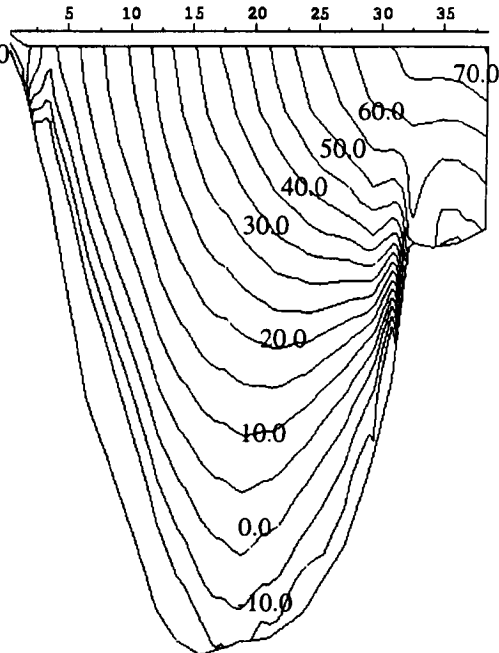
Cross-Section 1



Cross-Section 2

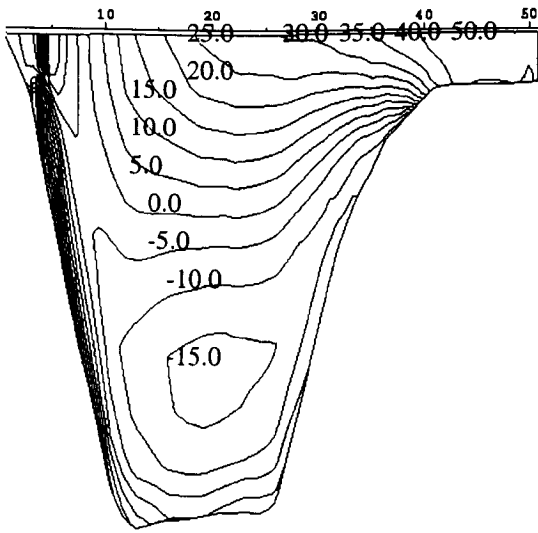


Cross-Section 3

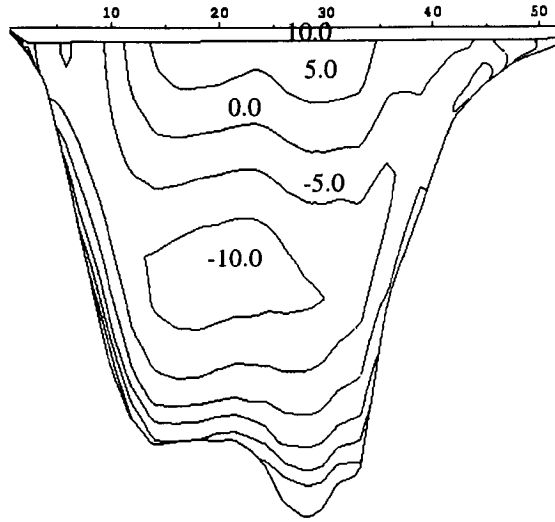


Cross-Section 4

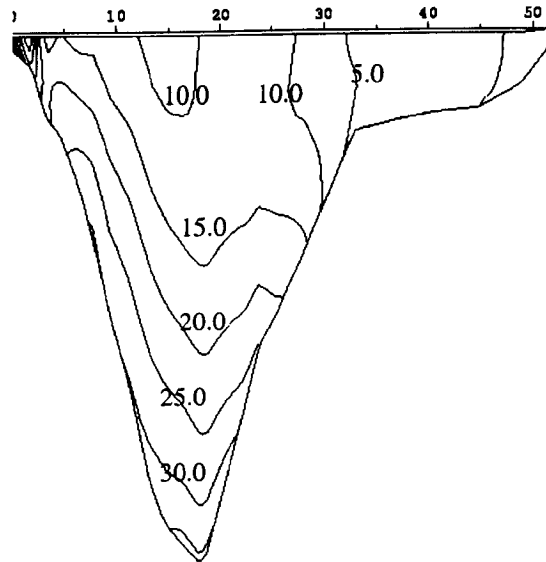
**Fig. 6.29 – River Severn TELEMAC Velocity Direction (deg.) at Cross-Sections 1, 2, 3 and 4 ( $C = 45 \text{ m}^{1/2}/\text{s}$  (MC) and  $35 \text{ m}^{1/2}/\text{s}$  (FP); Mesh S-2; Mixing-Length Model)**



Cross-Section 5

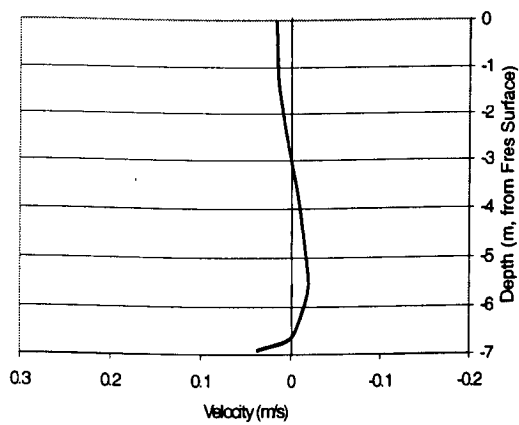


Cross-Section 6

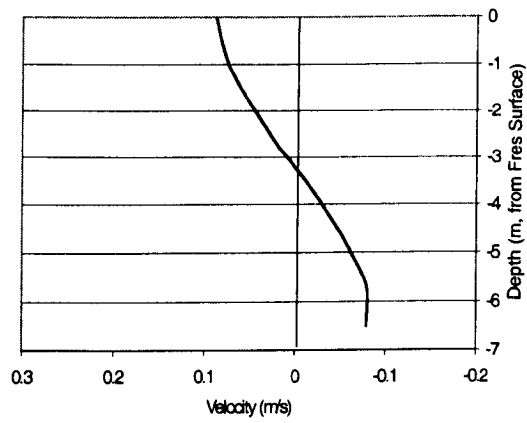


Cross-Section 7

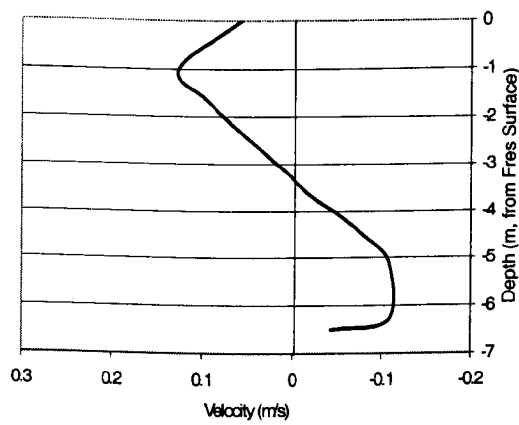
**Fig. 6.30 – River Severn TELEMAC Velocity Direction (deg.) at Cross-Sections 5, 6, and 7 ( $C = 45 \text{ m}^{1/2}/\text{s}$  (MC) and  $35 \text{ m}^{1/2}/\text{s}$  (FP); Mesh S-2; Mixing-Length Model)**



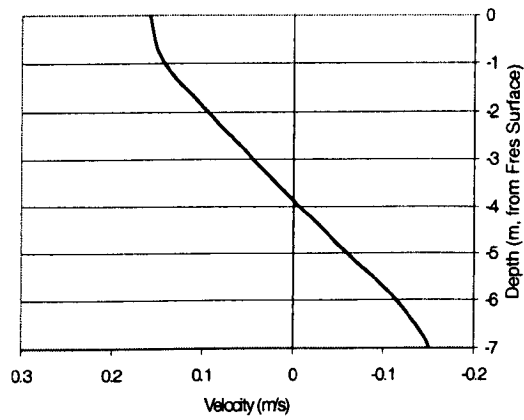
Cross-Section 1



Cross-Section 2

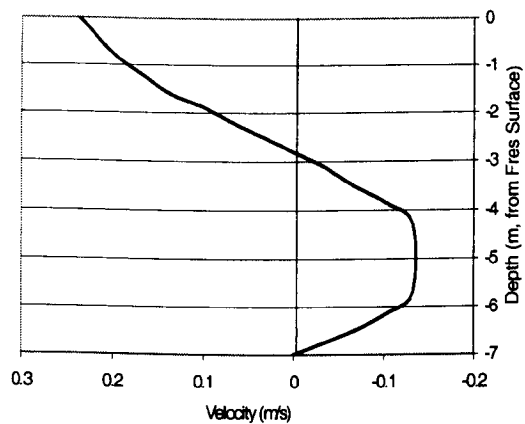


Cross-Section 3

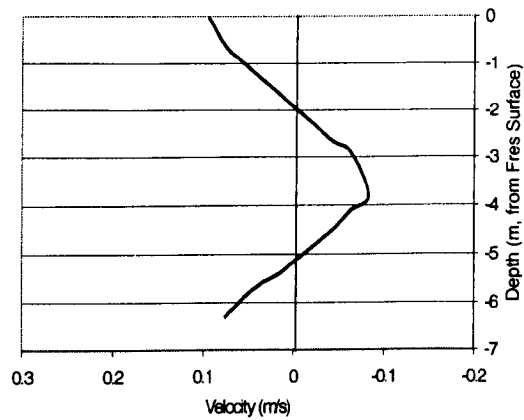


Cross-Section 4

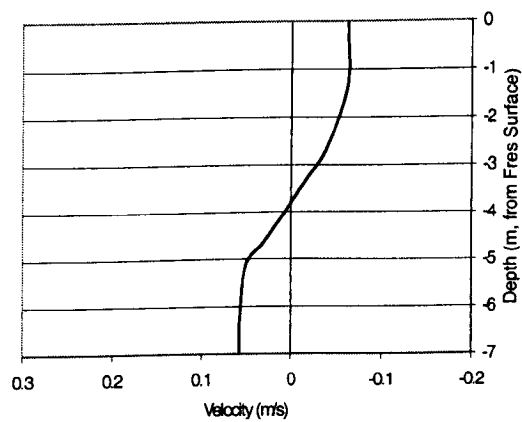
**Fig. 6.31 – River Severn TELEMAC Model: Recirculation at Cross-Sections 1 to 4**



Cross-Section 5



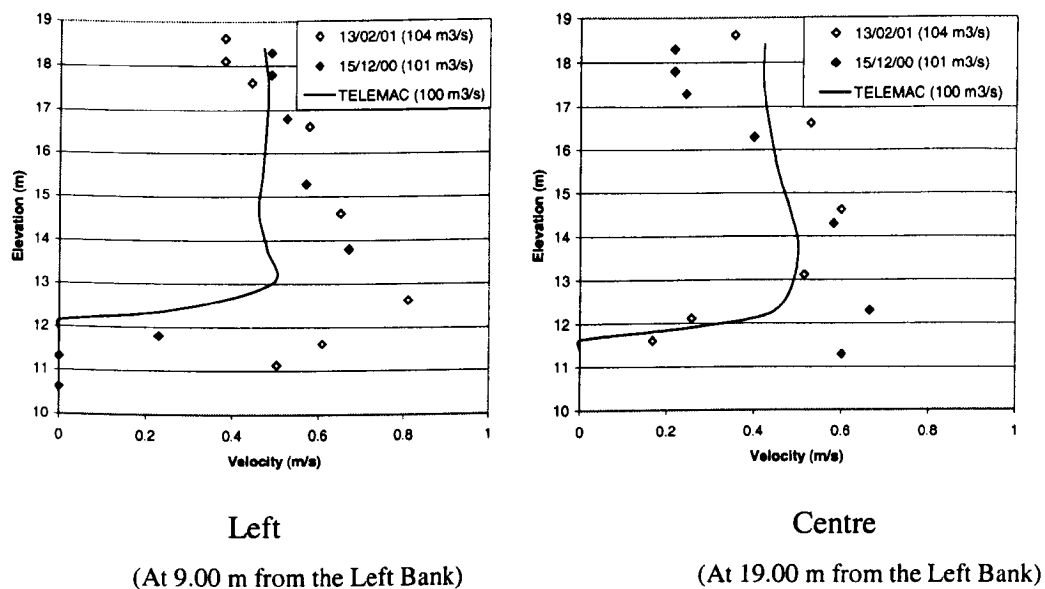
Cross-Section 6



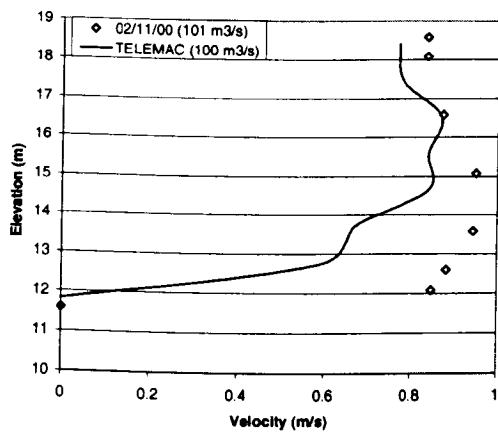
Cross-Section 7

**Fig. 6.32 – River Severn TELEMAC Model: Recirculation at Cross-Sections 5 to 7**

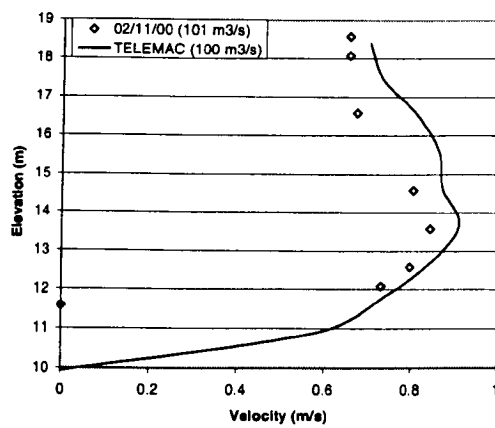




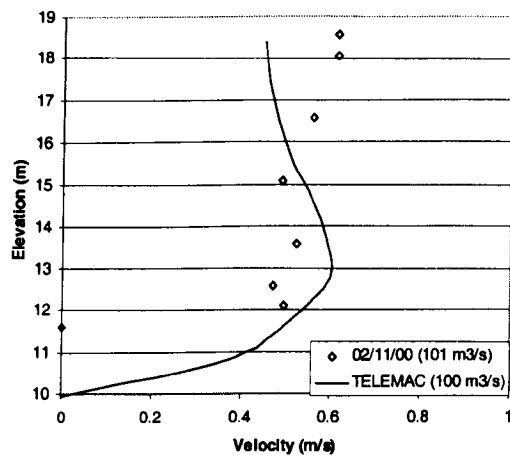
**Fig. 6.33 – River Severn: Comparison between Field Data and TELEMAC Predictions at Cross-Section 4**



Left  
(At 8.00 m from the Left Bank)

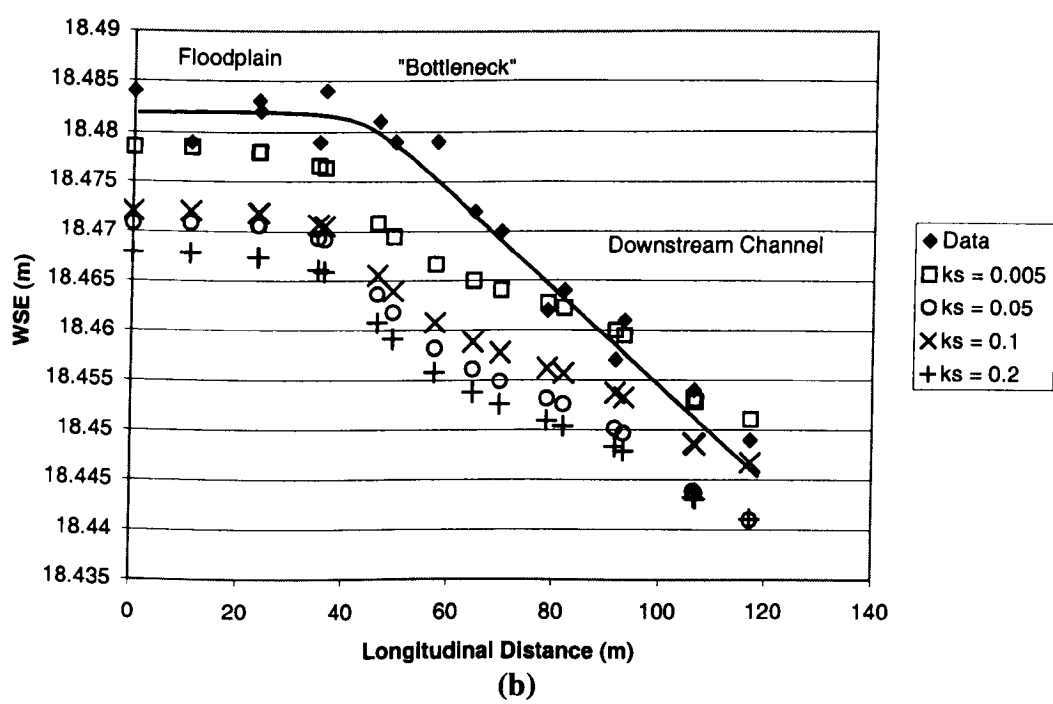
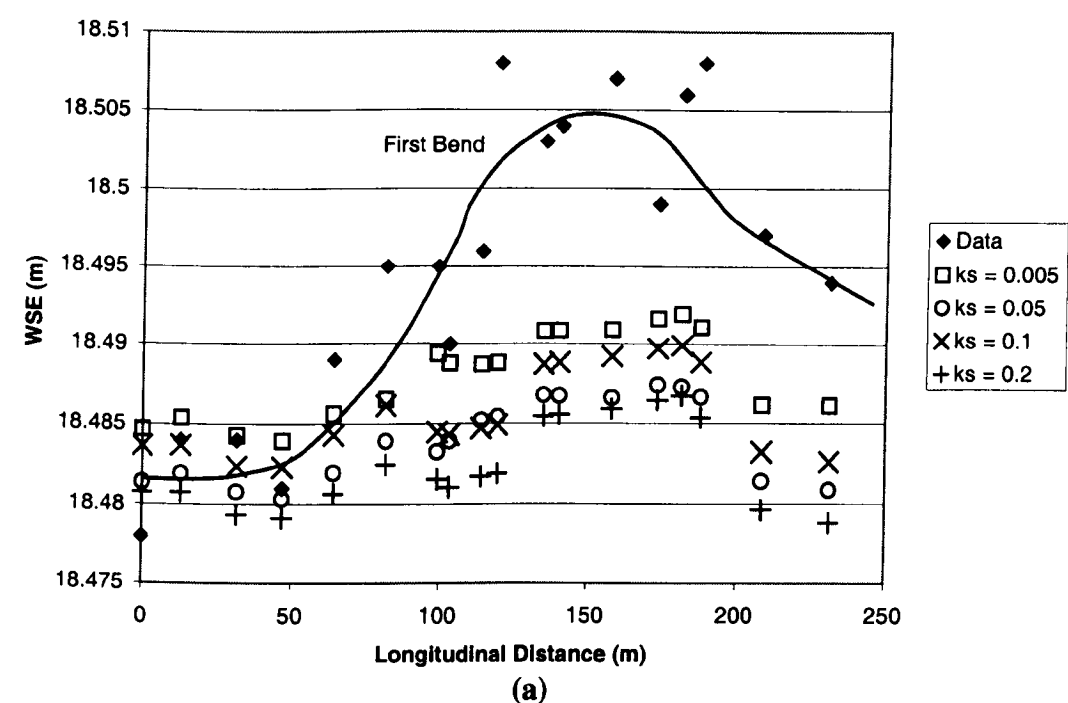


Left  
(At 12.00 m from the Left Bank)



Channel Centre  
(At 22.00 m from the Left Bank)

**Fig. 6.34 – River Severn: Comparison between Field Data and TELEMAC Predictions at Cross-Section 5**



**Fig. 6.35 – Comparison of Water Surface Elevation between CFX Models and Field Data (100 m<sup>3</sup>/s Event of Dec. 1999)**  
**(a) along the upstream first bend**  
**(b) along the right embankment**

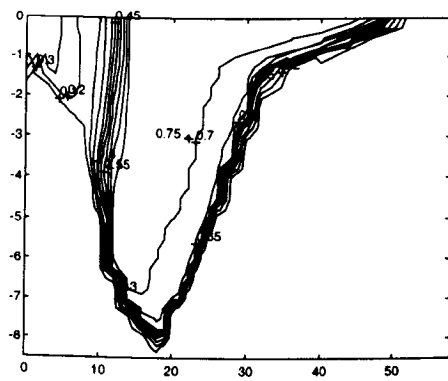


$k_s = 0.100$  m

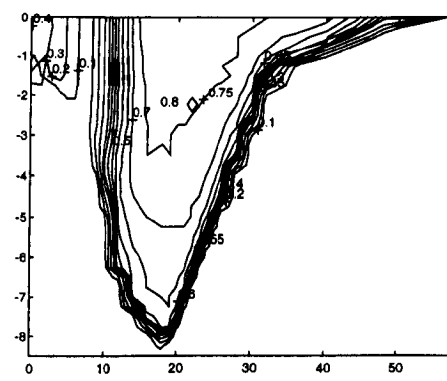


$k_s = 0.300$  m

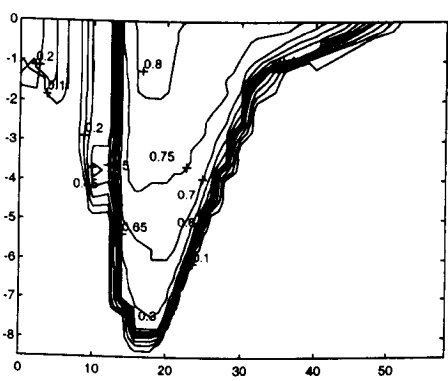
**Fig. 6.36 – Calculated CFX Pressure Field (Pa) on the Lid for Varying Roughness Values**



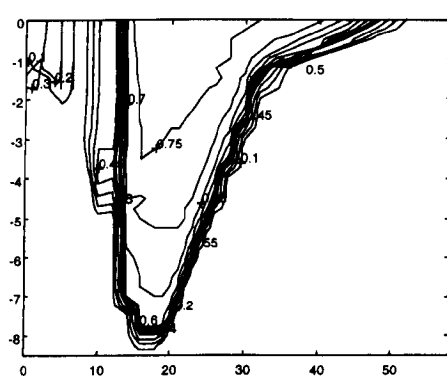
$k_s = 0.005$



$k_s = 0.050$

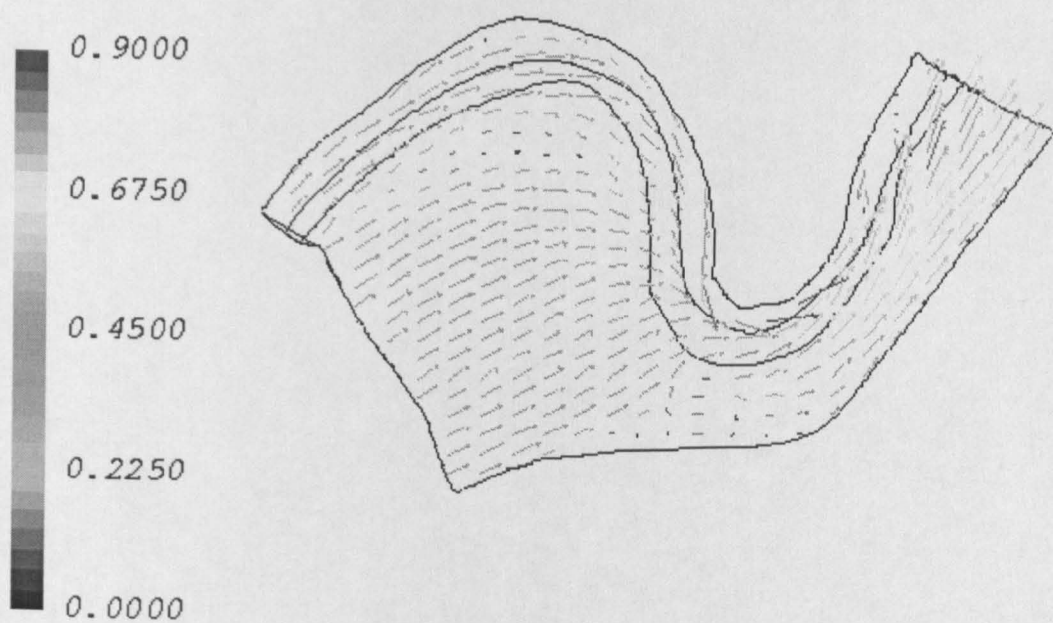


$k_s = 0.100$

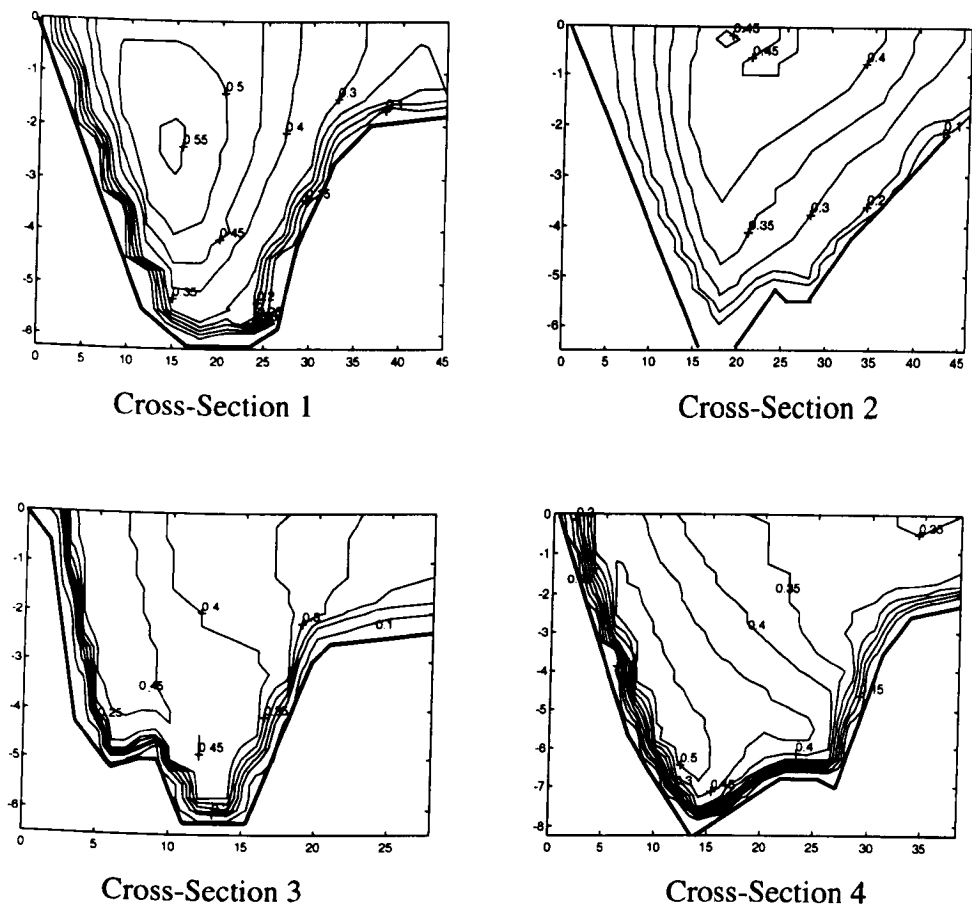


$k_s = 0.200$

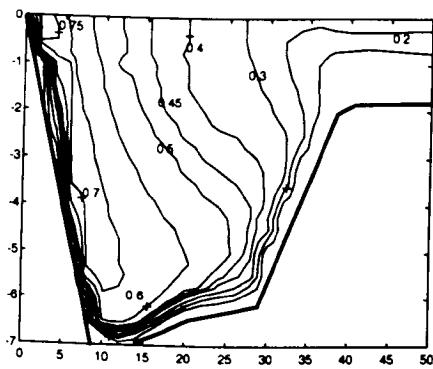
**Fig. 6.37 – River Severn CFX Velocity Profiles at Cross-Section 7 for Varying Roughness Values**



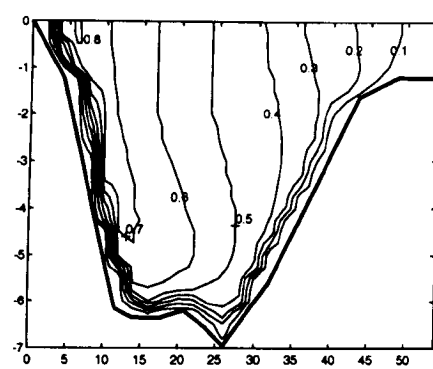
**Fig. 6.38 – River Severn CFX Velocity Vectors close to the Free Surface for a Flow of  $100 \text{ m}^3/\text{s}$**



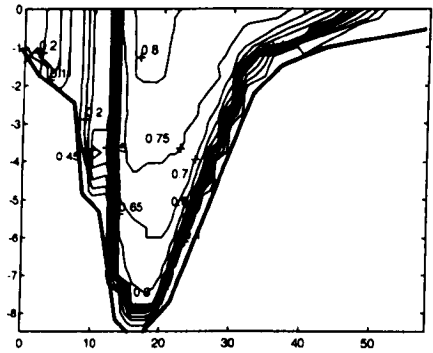
**Fig. 6.39 – River Severn CFX Velocity Profile (m/s) at Cross-Sections 1, 2, 3 and 4 ( $k_s = 0.100$  m, Grid CFX S-1,  $k-\varepsilon$  model)**



Cross-Section 5



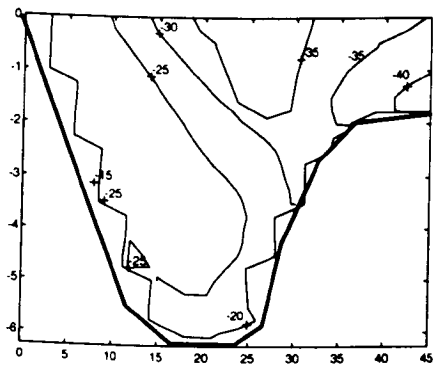
Cross-Section 6



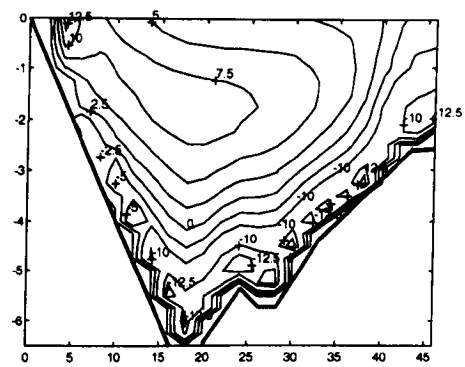
Cross-Section 7

**Fig. 6.40 – River Severn CFX Velocity Profile (m/s) at Cross-Sections 5, 6 and 7  
( $k_s = 0.100$  m, Grid CFX S-1,  $k-\epsilon$  model)**

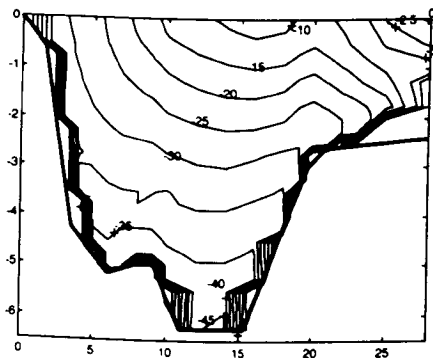




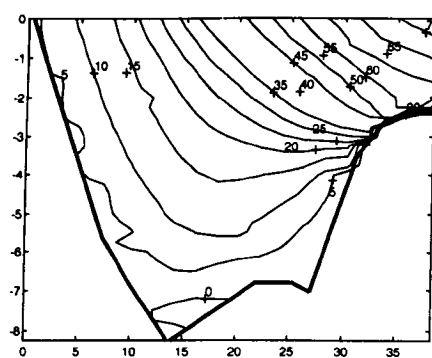
Cross-Section 1



Cross-Section 2

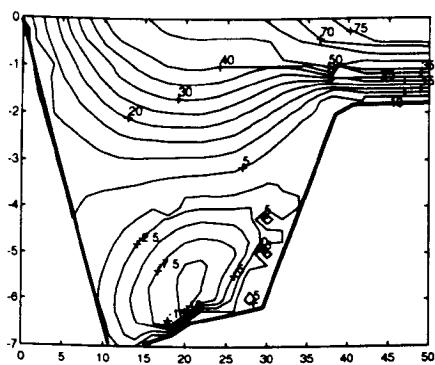


Cross-Section 3

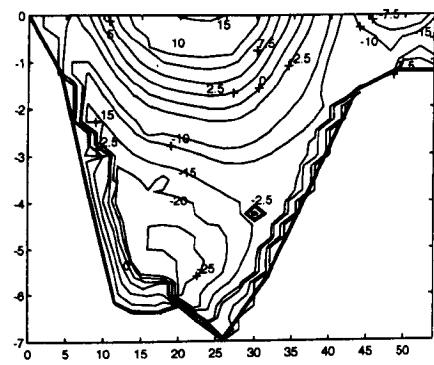


Cross-Section 4

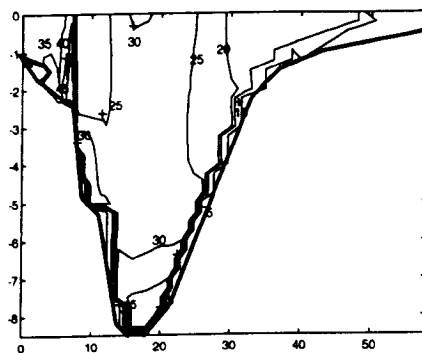
**Fig. 6.41 – River Severn CFX Velocity Direction (deg.) at Cross-Sections 1, 2, 3 and 4 ( $k_s = 0.100$  m, Grid CFX S-1,  $k-\epsilon$  model)**



Cross-Section 5

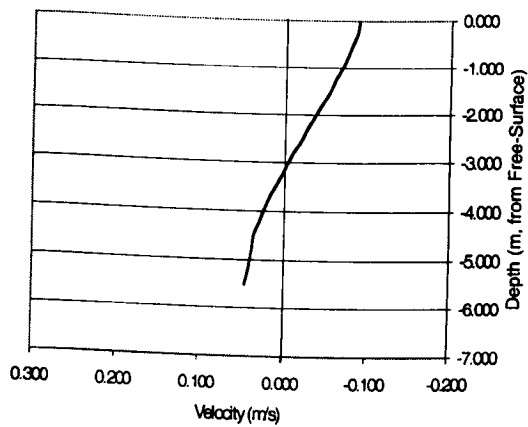


Cross-Section 6

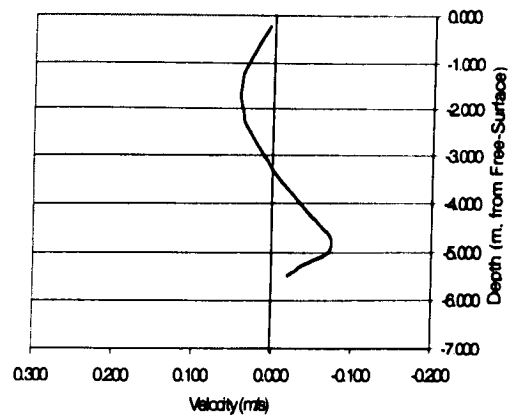


Cross-Section 7

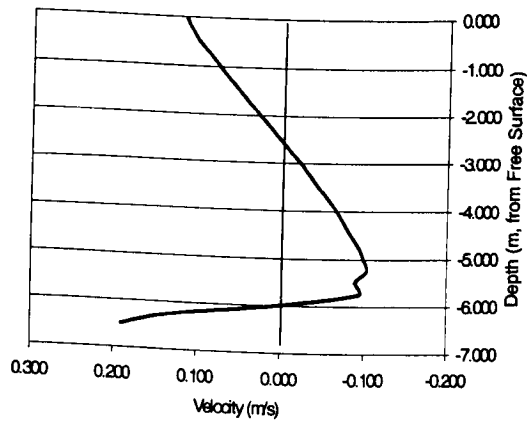
**Fig. 6.42 – River Severn CFX Velocity Orientation (deg.) at Cross-Sections 5, 6 and 7 ( $k_s = 0.100$  m, Grid CFX S-1,  $k-\epsilon$  model)**



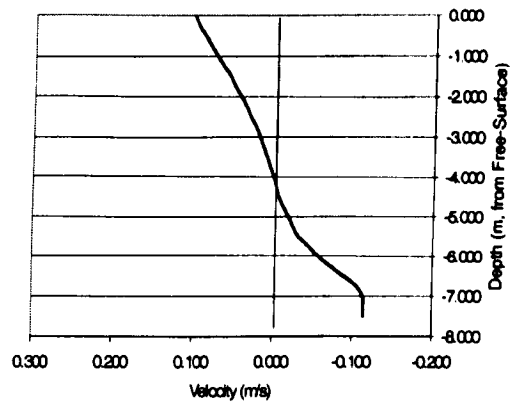
Cross-Section 1



Cross-Section 2

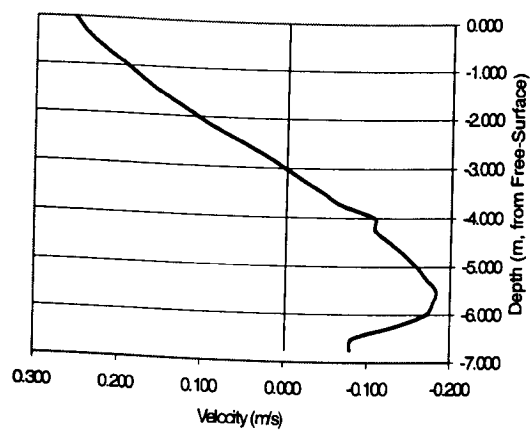


Cross-Section 3

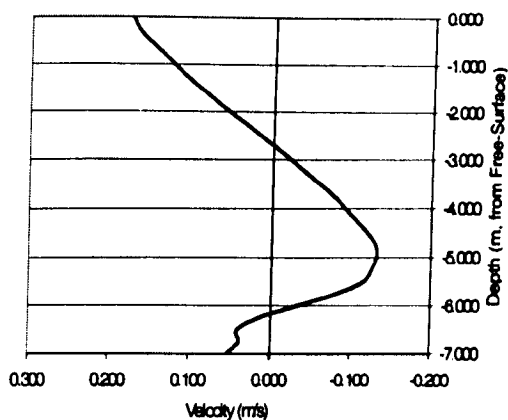


Cross-Section 4

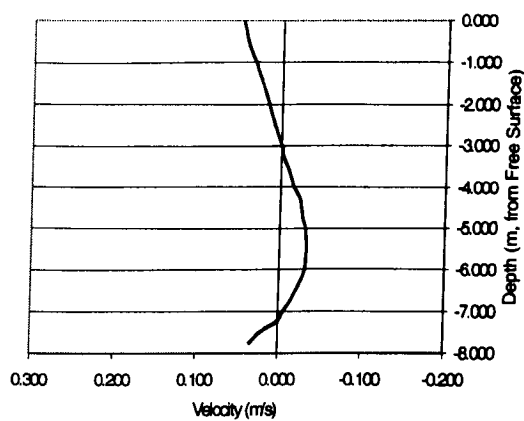
**Fig. 6.43 – River Severn CFX Model: River Severn CFX Model: Calculated Recirculation (m/s) at Sections 1, 2, 3 and 4**



Cross-Section 5

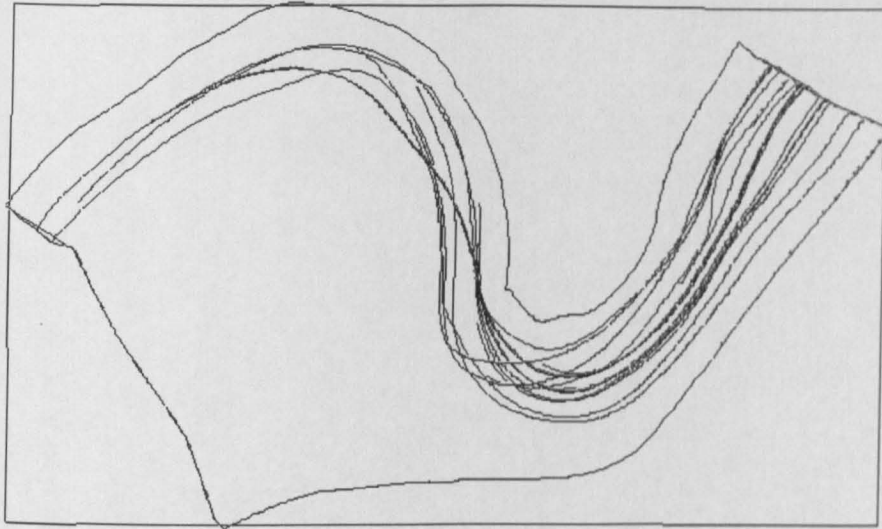


Cross-Section 6



Cross-Section 7

**Fig. 6.44 – River Severn CFX Model: River Severn CFX Model: Calculated Recirculation (m/s) at Sections 5, 6 and 7**

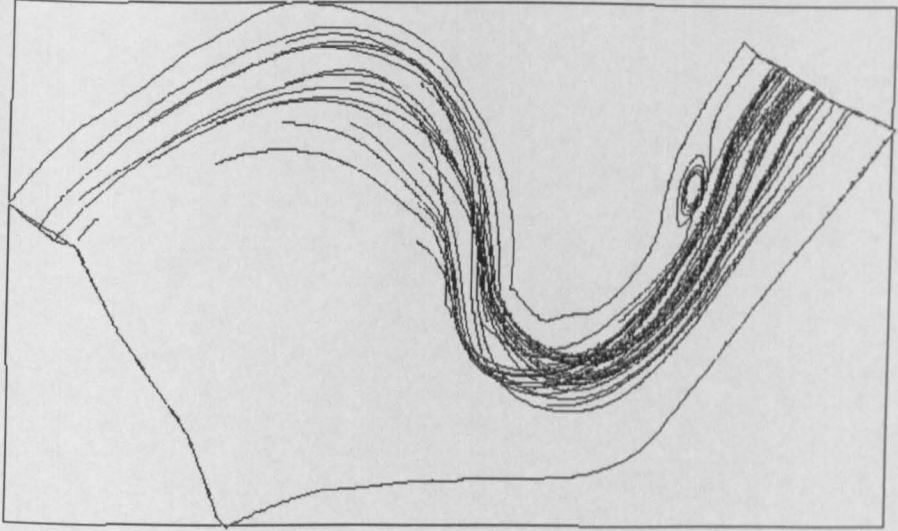


(a)



(b)

**Fig. 6.45 – CFX Numerical Tracer Release at Elevation 13.0 m in the Severn:**  
**(a) Tracer Route**  
**(b) Rotational Effects and Velocity**

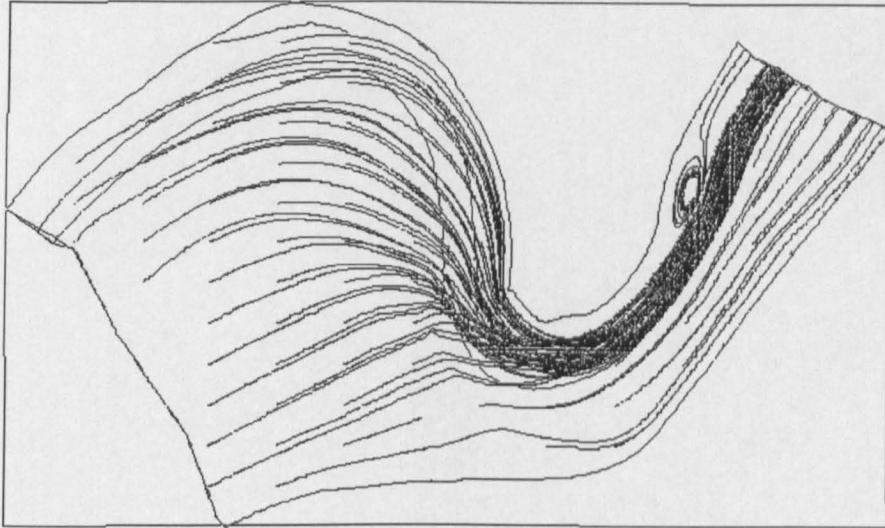


(a)

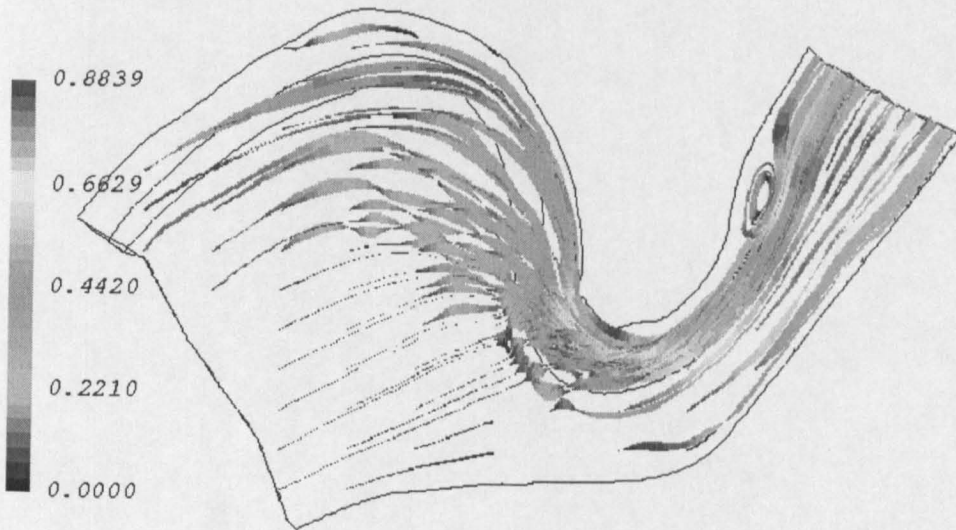


(b)

**Fig. 6.46 – CFX Numerical Tracer Release at Elevation 16.5 m in the Severn:**  
 (a) Tracer Route  
 (b) Rotational Effects and Velocity



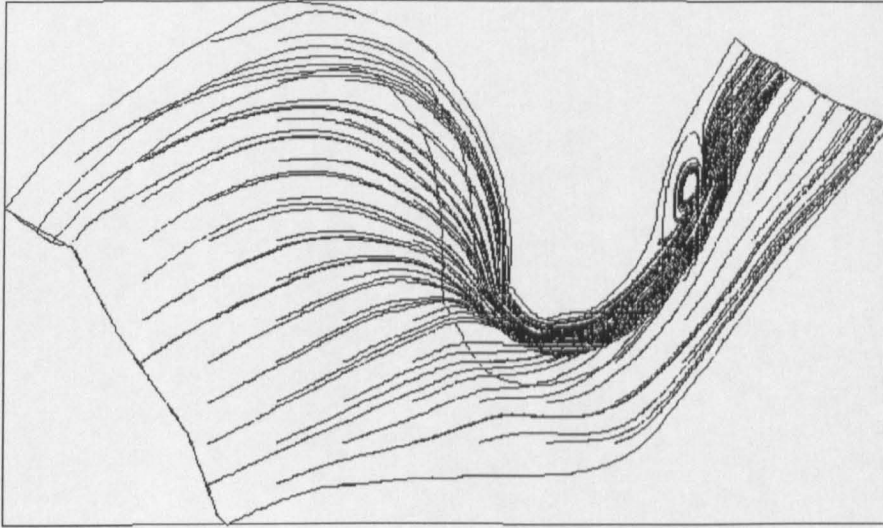
(a)



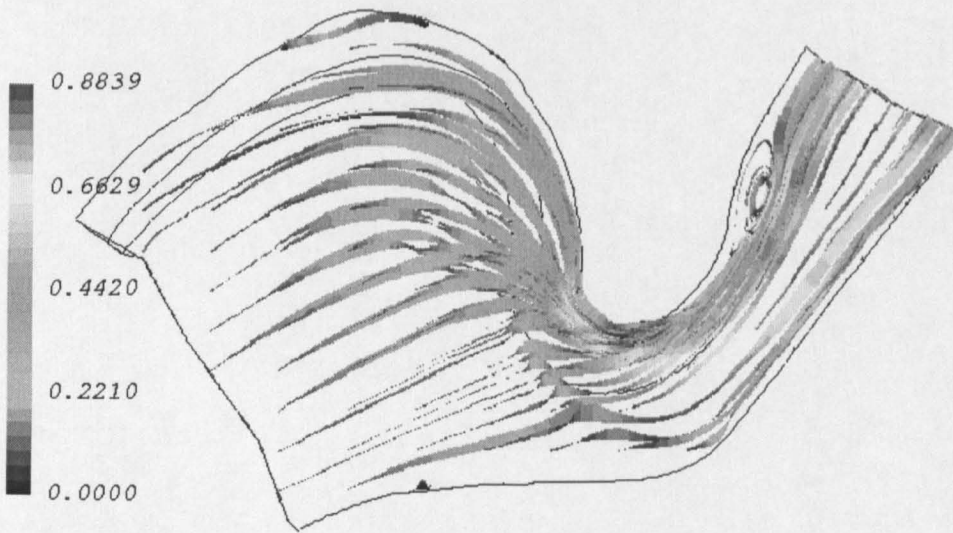
(b)

**Fig. 6.47 – CFX Numerical Tracer Release at Elevation 17.9 m in the Severn:**  
**(a) Tracer Route**  
**(b) Rotational Effects and Velocity**





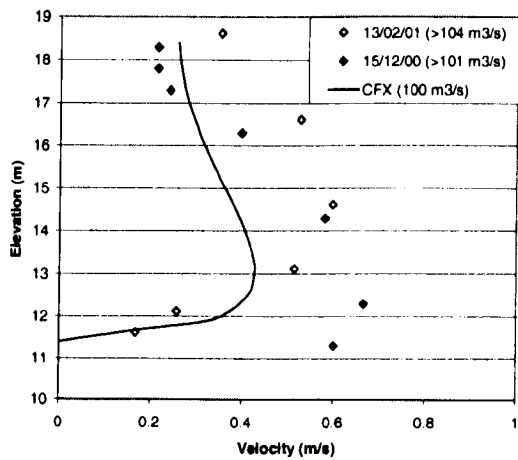
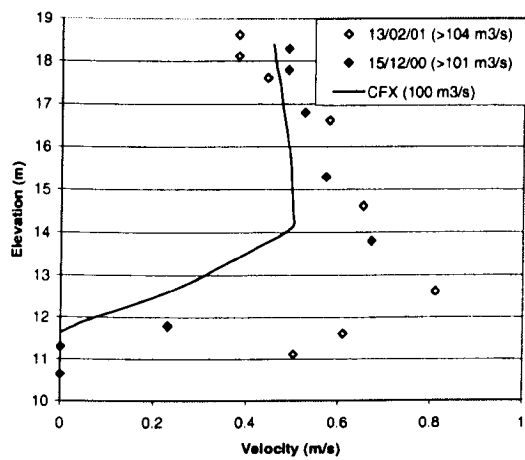
(a)



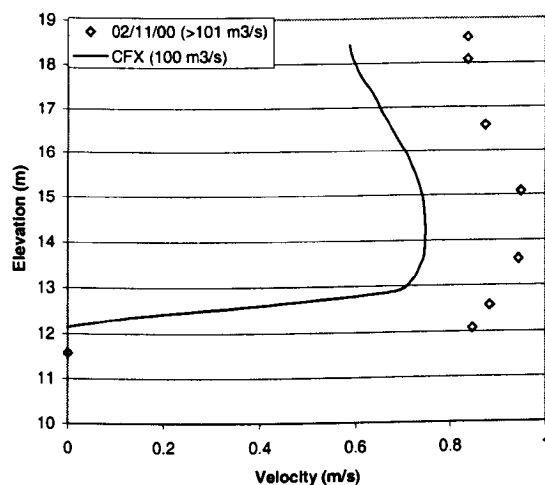
(b)

**Fig. 6.48 – CFX Numerical Tracer Release at Elevation 18.3 m in the Severn:**  
**(a) Tracer Route**  
**(b) Rotational Effects and Velocity**

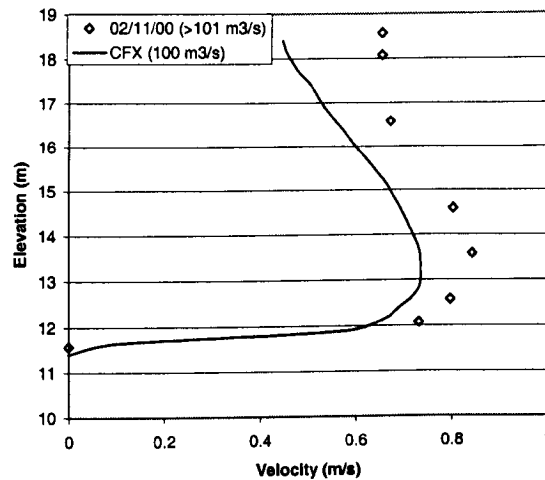




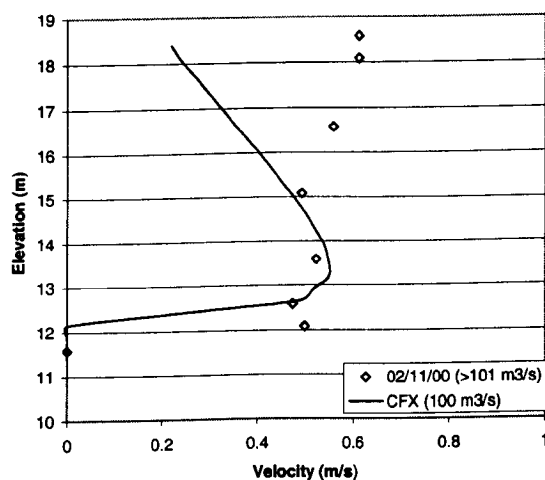
**Fig. 6.49 – Comparison between Field Data and River Severn CFX Model Predictions at Cross-Section 4**



At 8.00 m from the Left Bank

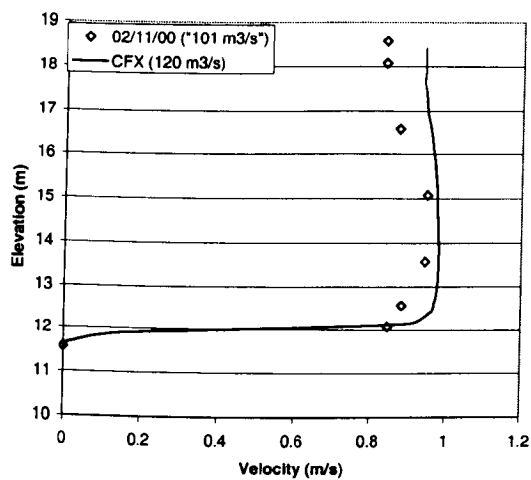


At 12.00 m from the Left Bank

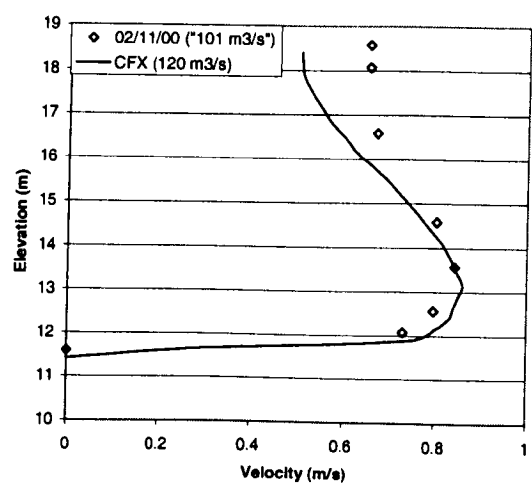


At 22.00 m from the Left Bank

**Fig. 6.50 – Comparison between Field Data and River Severn CFX Model Predictions at Cross-Section 5**

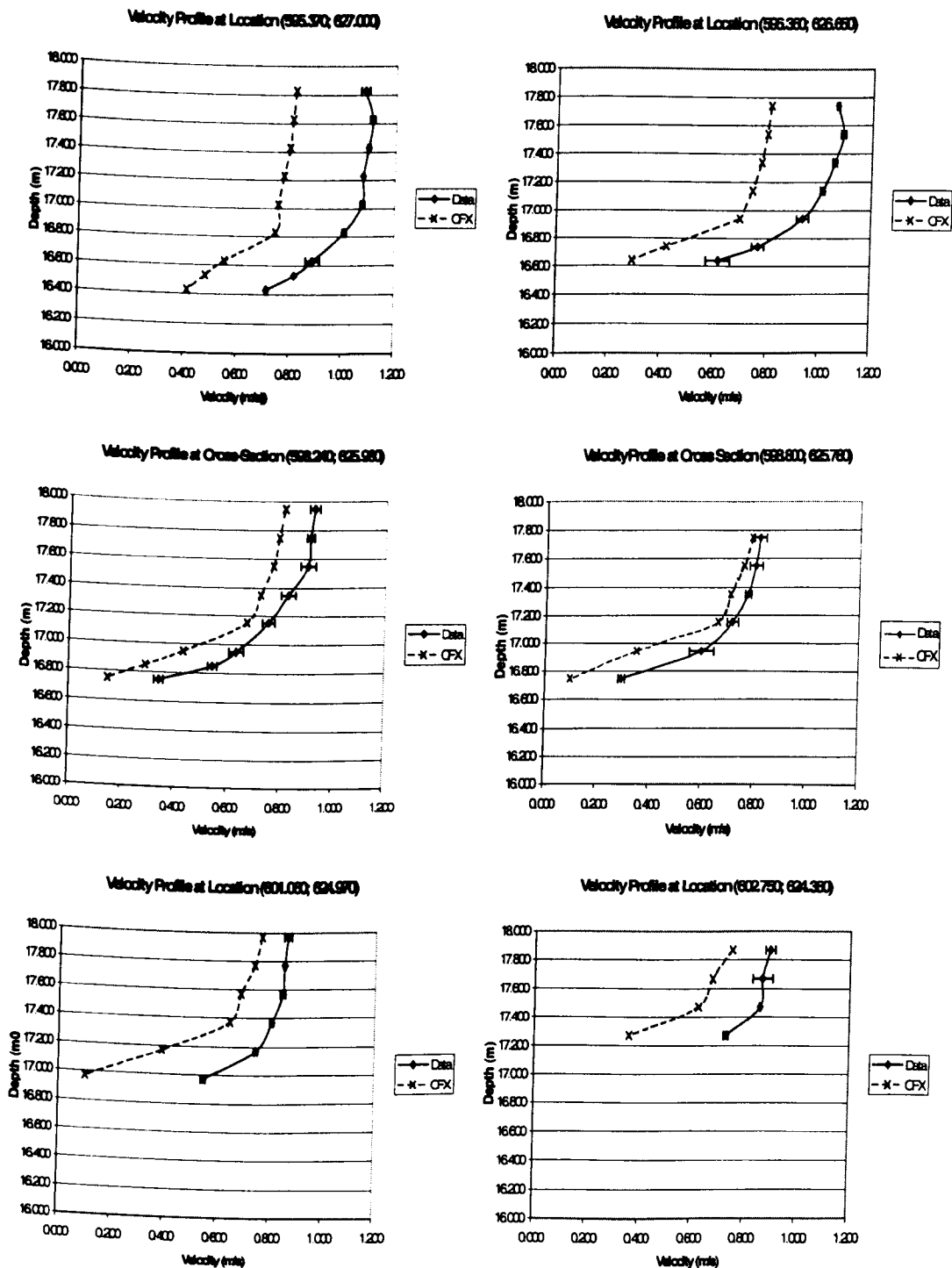


At 8.00 m from the Left Bank

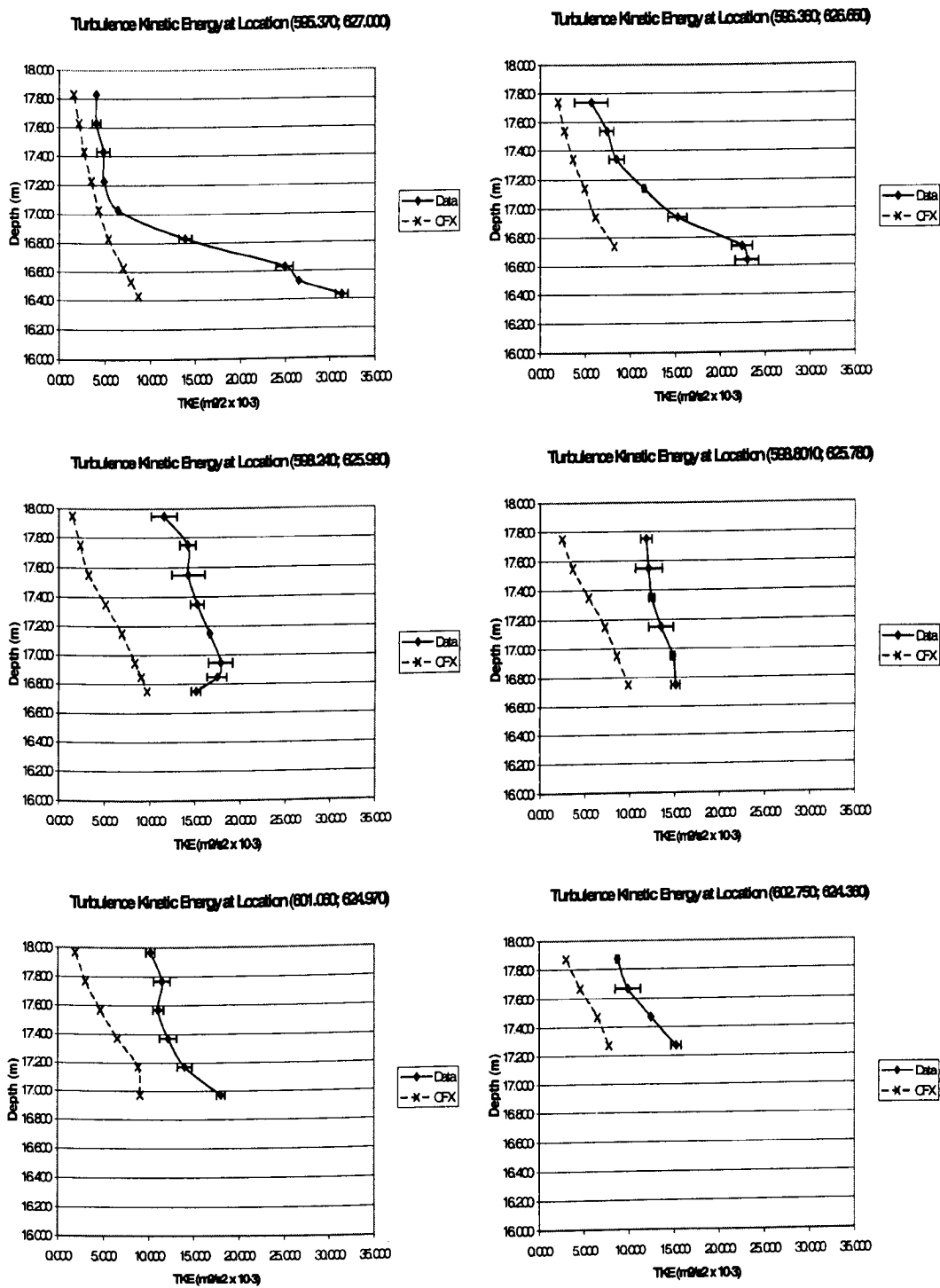


At 12.00 m from the Left Bank

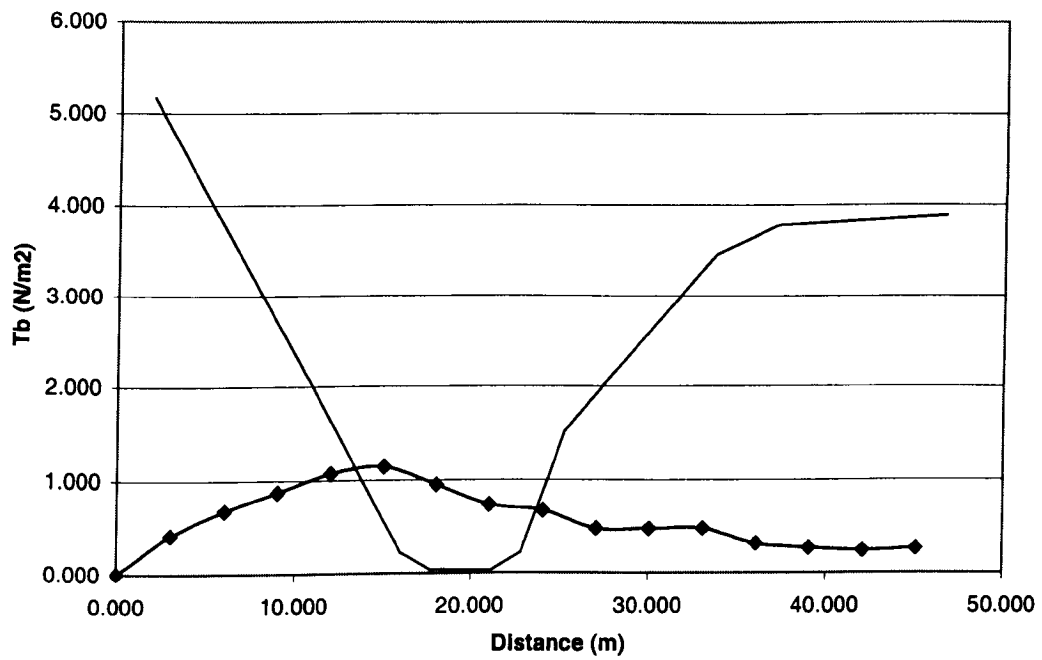
**Fig. 6.51 – Comparison between Field Data and River Severn CFX Model Predictions at Cross-Section 5 for a Flow of 120 m<sup>3</sup>/s (Discharge + 20%)**



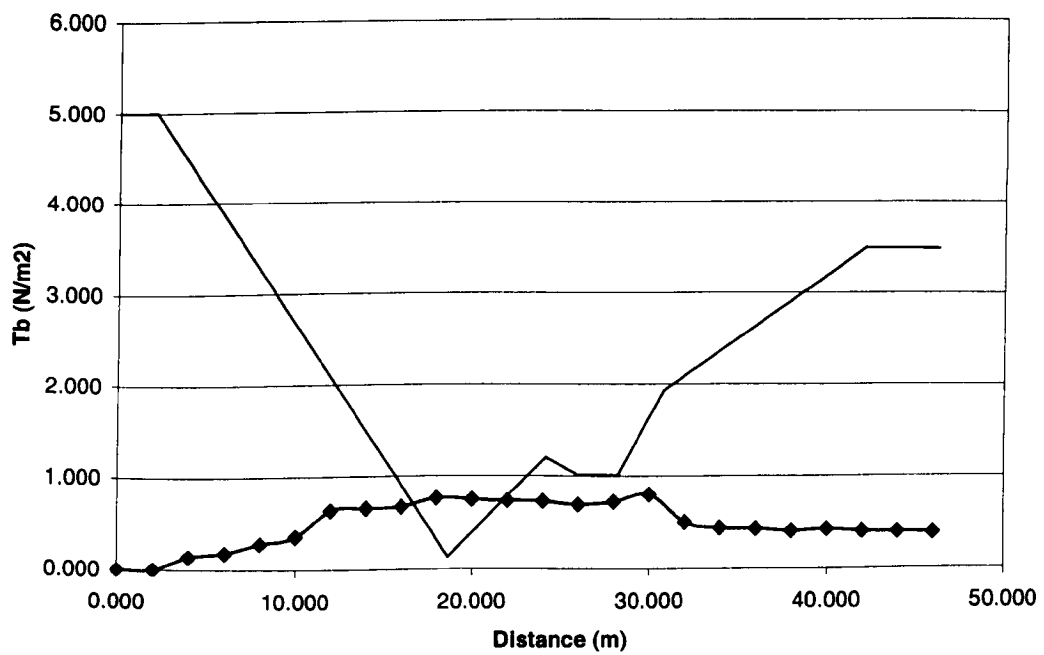
**Fig. 6.52 – Comparison between Measured and Predicted Velocity Profiles along the Severn Main Channel Right Bank, at the Tower (m/s; March 2000)**



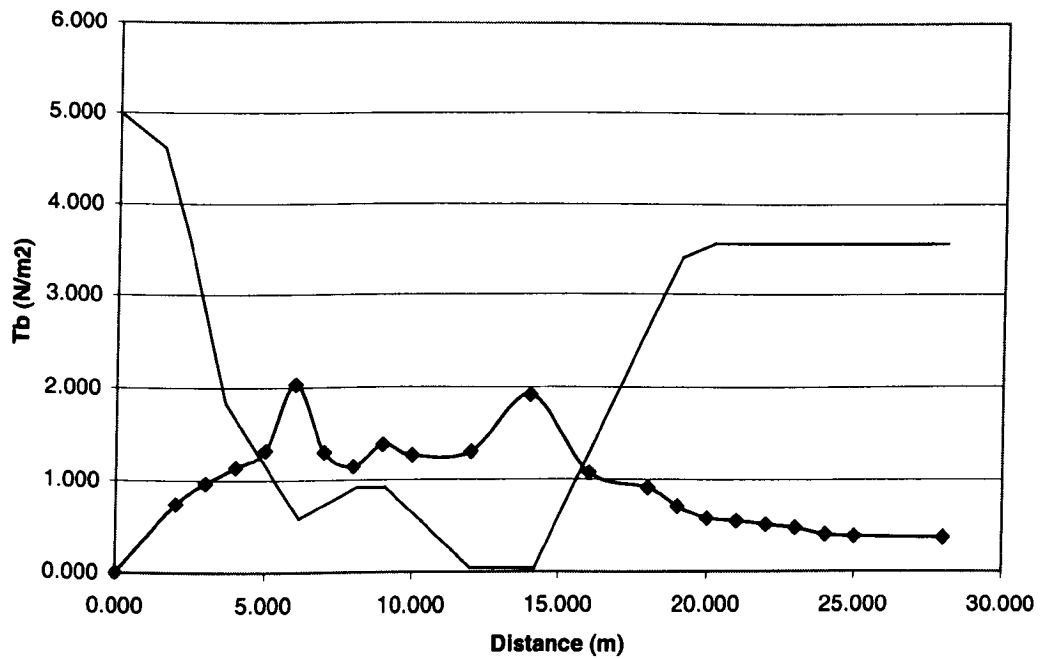
**Fig. 6.53– Comparison between Measured and Predicted Turbulence Kinetic Energy along the Severn Main Channel Right Bank, at the Tower ( $\text{m}^2/\text{s}^2$ ; March 2000)**



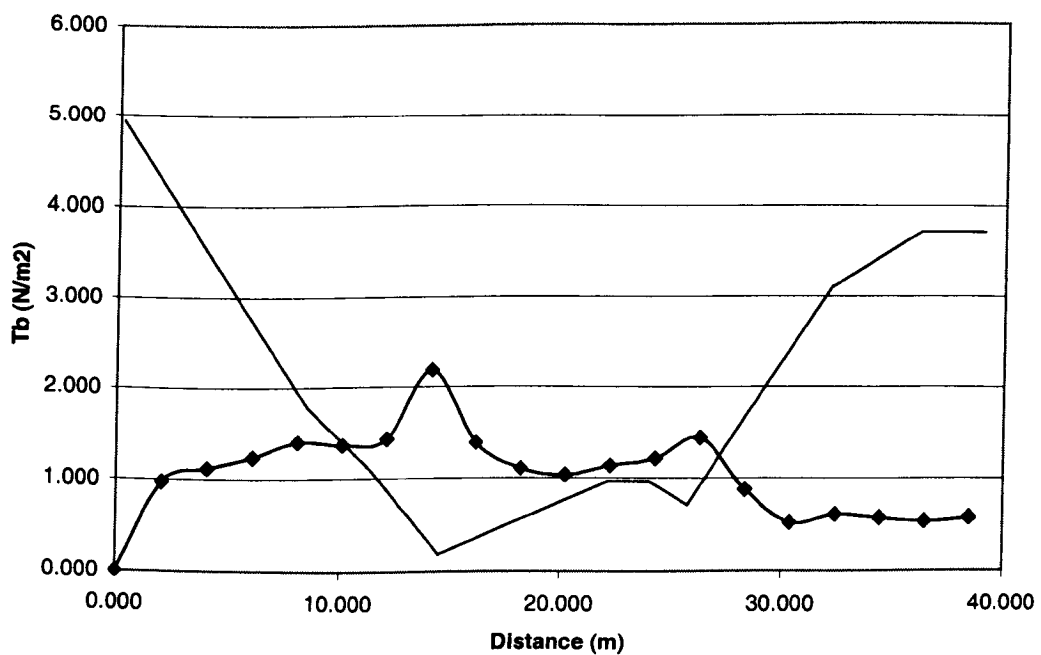
**Fig. 6.54 – Calculated Bed Shear Stresses at Section 1 from CFX River Severn Model ( $k-\epsilon$  model)**



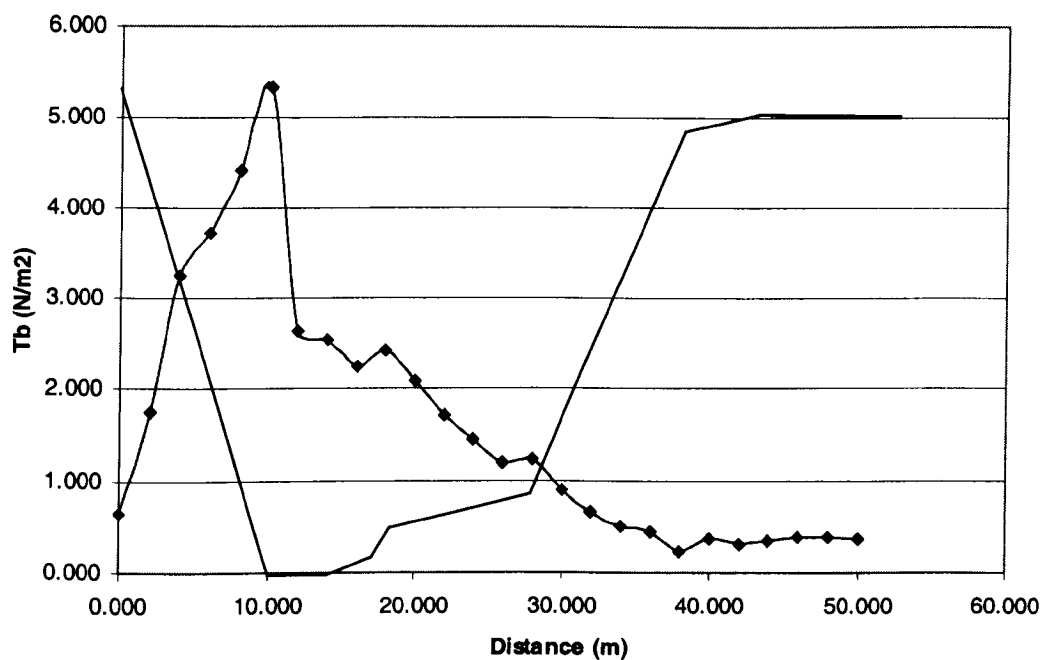
**Fig. 6.55 – Calculated Bed Shear Stresses at Section 2 from CFX River Severn Model ( $k-\epsilon$  model)**



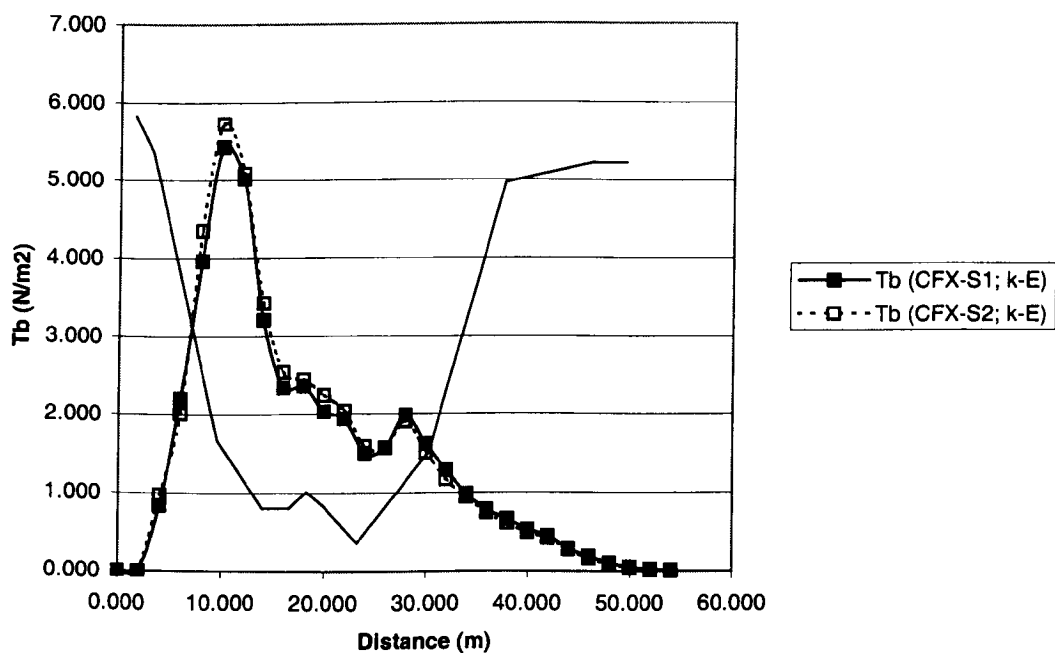
**Fig. 6.56 – Calculated Bed Shear Stresses at Section 3 from CFX River Severn Model ( $k-\epsilon$  model)**



**Fig. 6.57 – Calculated Bed Shear Stresses at Section 4 from CFX River Severn Model ( $k-\epsilon$  model)**

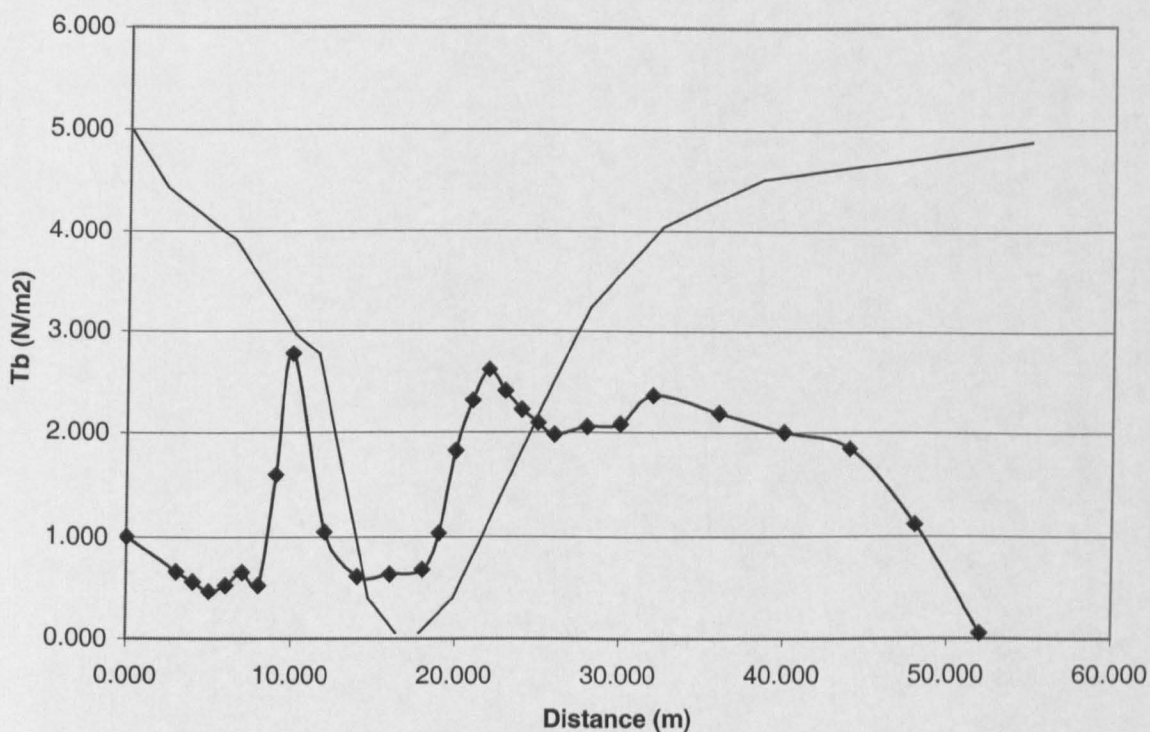


**Fig. 6.58 – Calculated Bed Shear Stresses at Section 5 from CFX River Severn Model ( $k-\varepsilon$  model)**

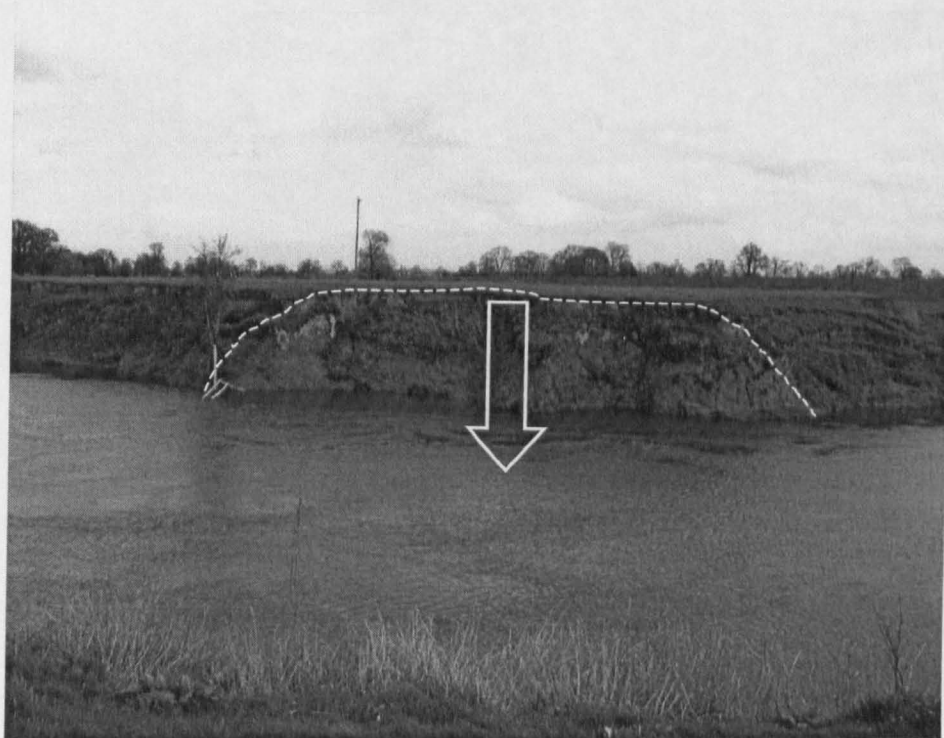


**Fig. 6.59 – Calculated Bed Shear Stresses at Section 6 from CFX River Severn Model for the Two CFX Grids ( $k-\varepsilon$  model)**

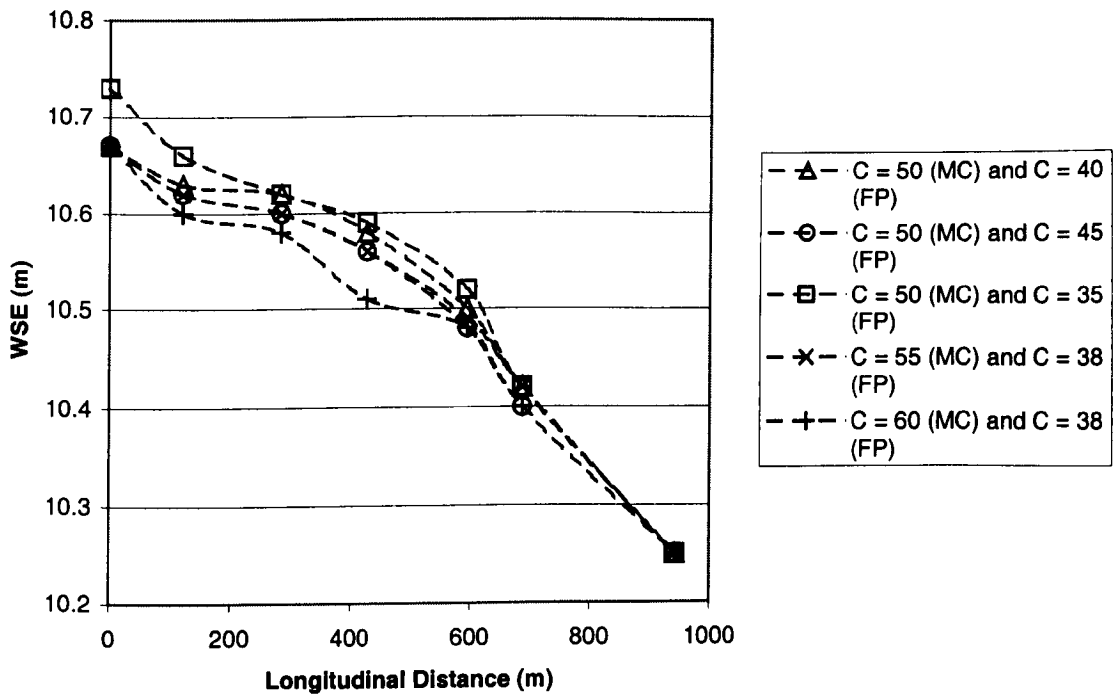




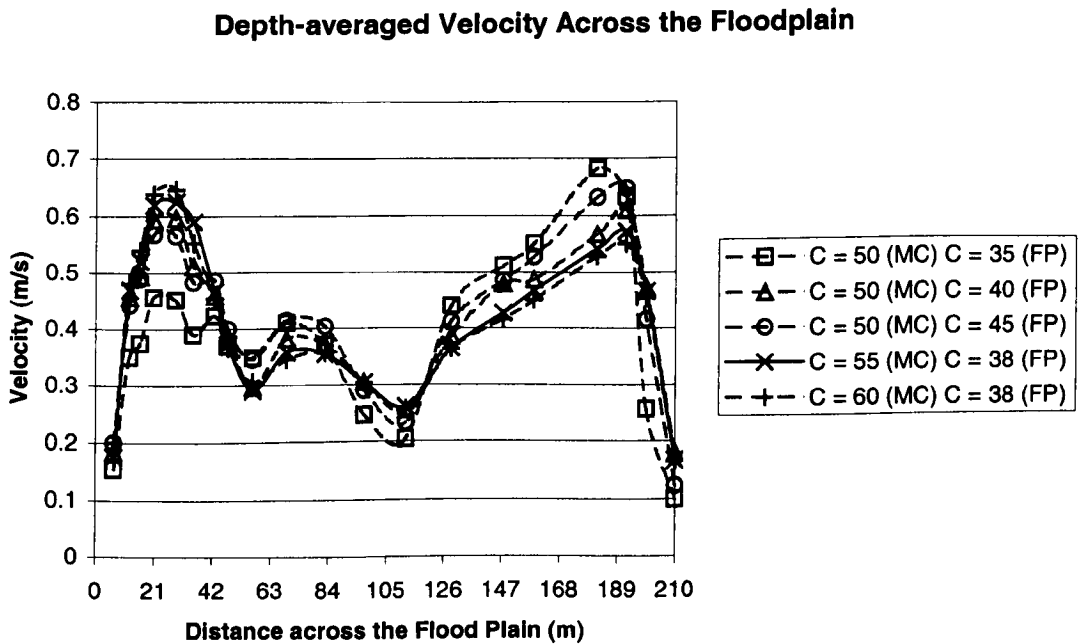
**Fig. 6.60 – Calculated Bed Shear Stresses at Section 7 from CFX River Severn Model ( $k-\varepsilon$  model)**



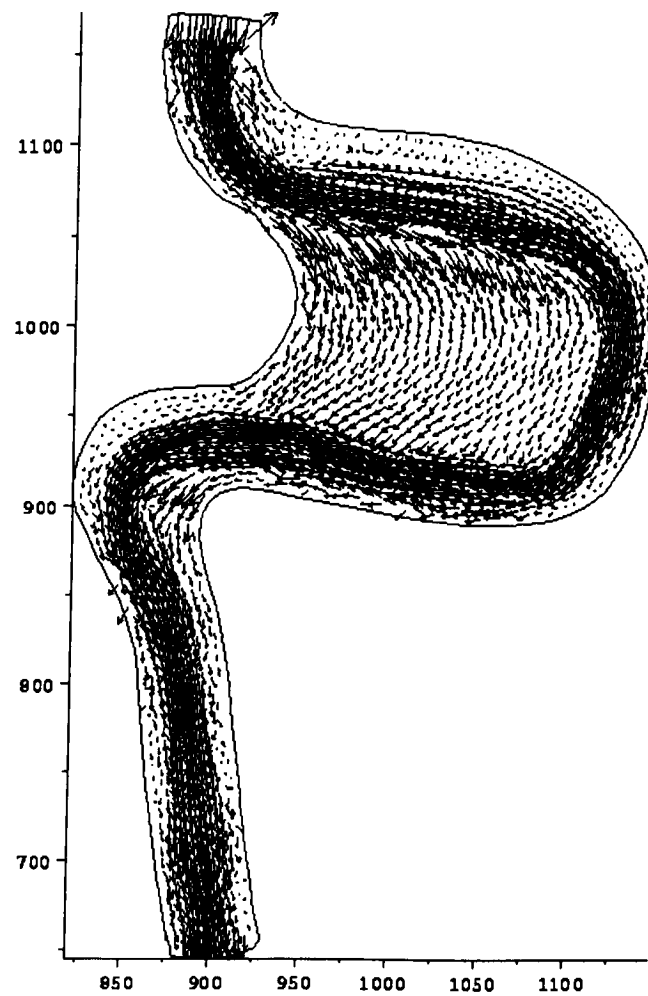
**Fig. 6.61 – River Severn: Bank Collapse at the Inner Bank of the Second Meander**



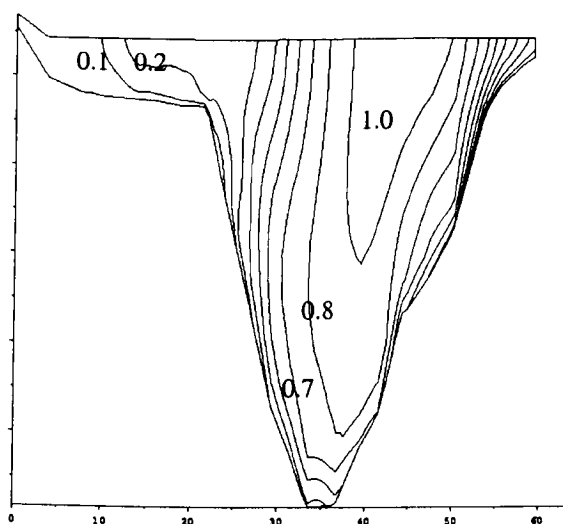
**Fig. 6.62 – TELEMAC Model of the Ribble: Sensitivity Analysis of the Free Surface to Roughness**



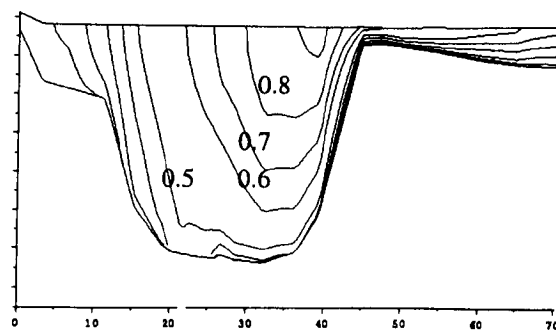
**Fig. 6.63 – TELEMAC Model of the Ribble: Impact of Roughness on Velocity Distribution across the Flood Plain**



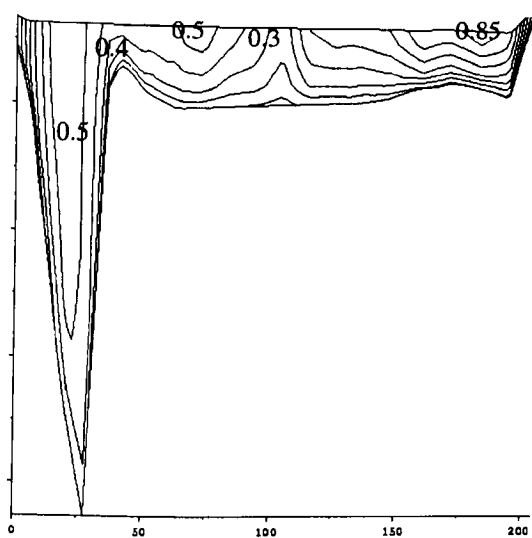
**Fig. 6.64 – River Ribble TELEMAC Depth-Averaged Velocity Vectors for a Flow of  $98 \text{ m}^3/\text{s}$**



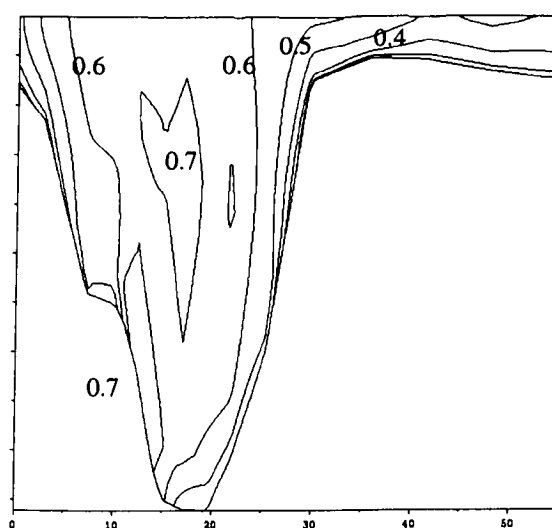
Cross-Section 1



Cross-Section 2

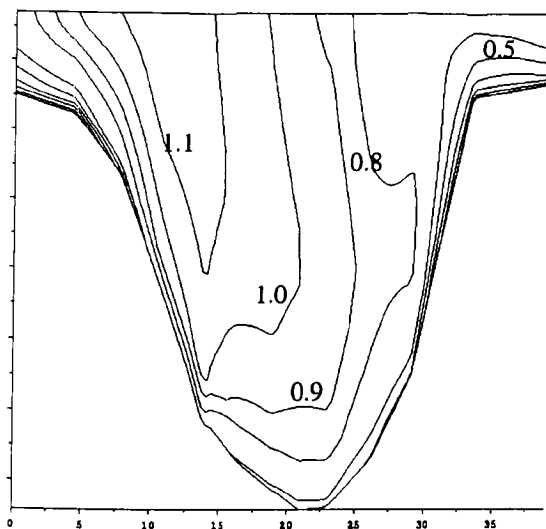


Cross-Section 3

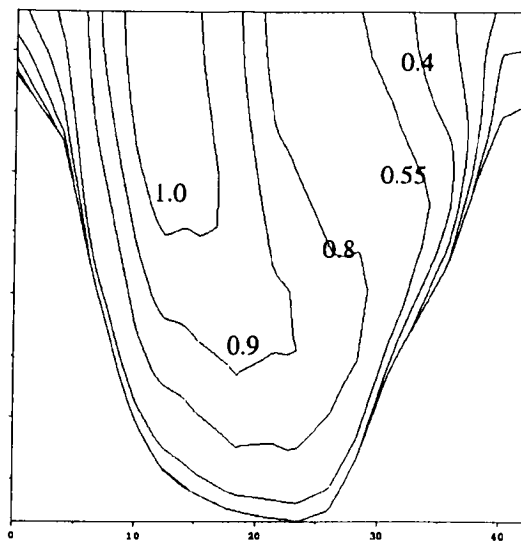


Cross-Section 4

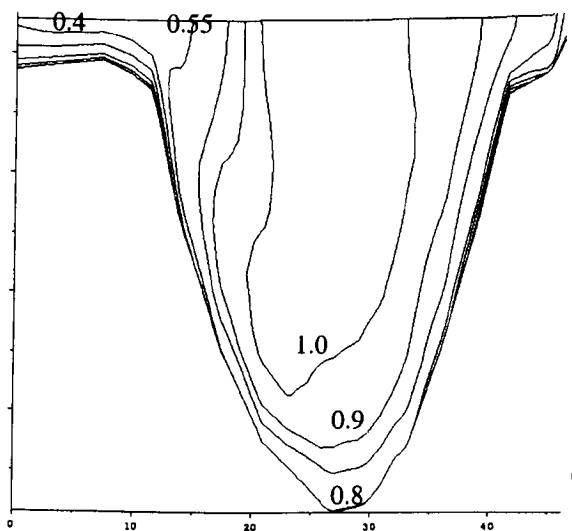
**Fig. 6.65 – River Ribble TELEMAC Velocity Profile (m/s) at Cross-Sections 1, 2, 3 and 4 ( $C = 38 \text{ m}^{1/2}/\text{s}$  on the flood plain,  $C = 50 \text{ m}^{1/2}/\text{s}$  in the main Channel, mixing-length model)**



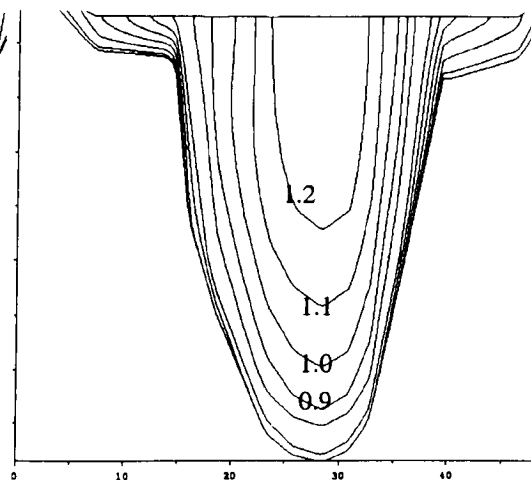
Cross-Section 5



Cross-Section 6

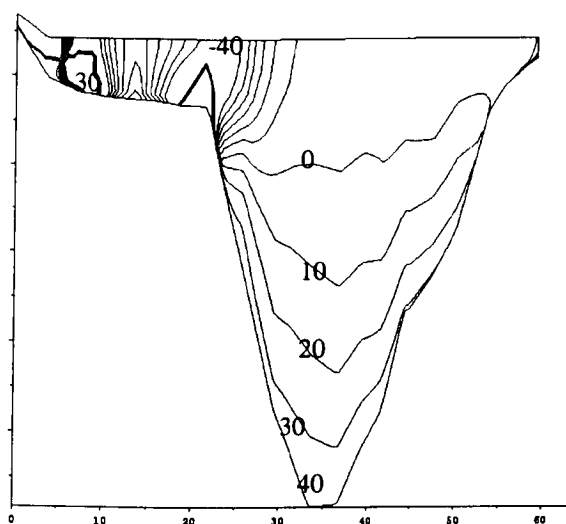


Cross-Section 7

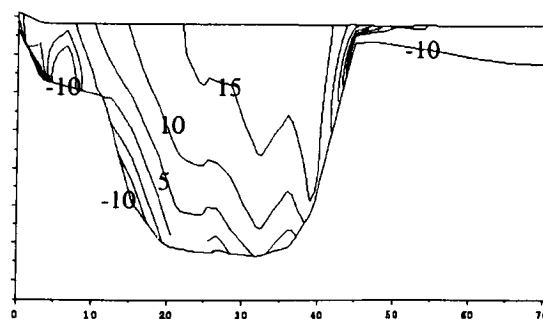


Cross-Section 8

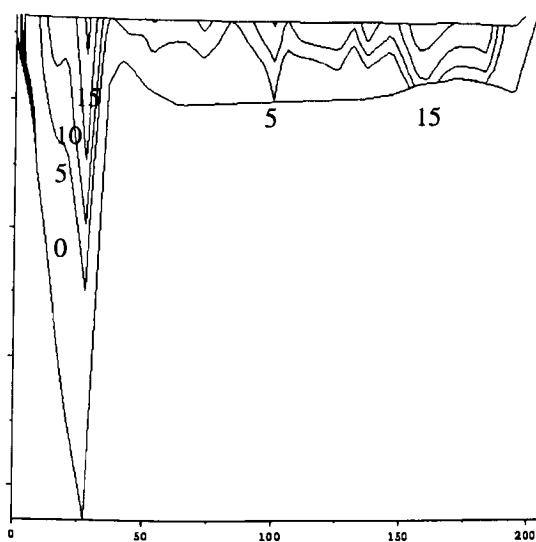
**Fig. 6.66– River Ribble TELEMAC Velocity Profile (m/s) at Cross-Sections 5, 6, 7 and 8 ( $C = 38 \text{ m}^{1/2}/\text{s}$  on the flood plain,  $C = 55 \text{ m}^{1/2}/\text{s}$  in the main Channel, mixing-length model)**



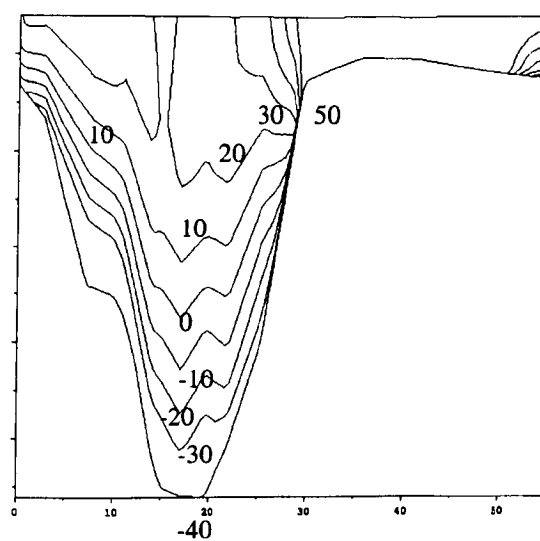
Cross-Section 1



Cross-Section 2

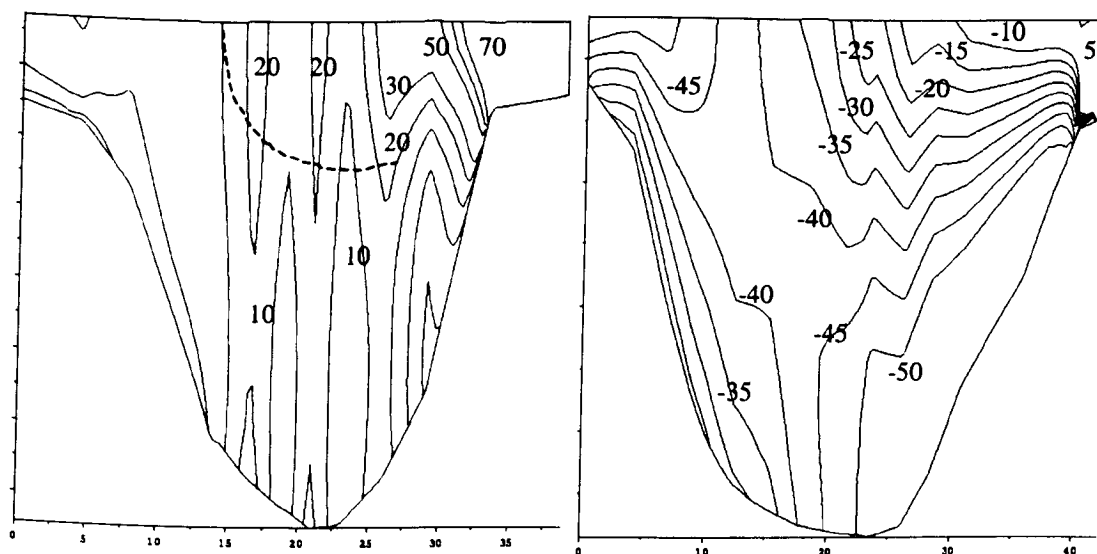


Cross-Section 3



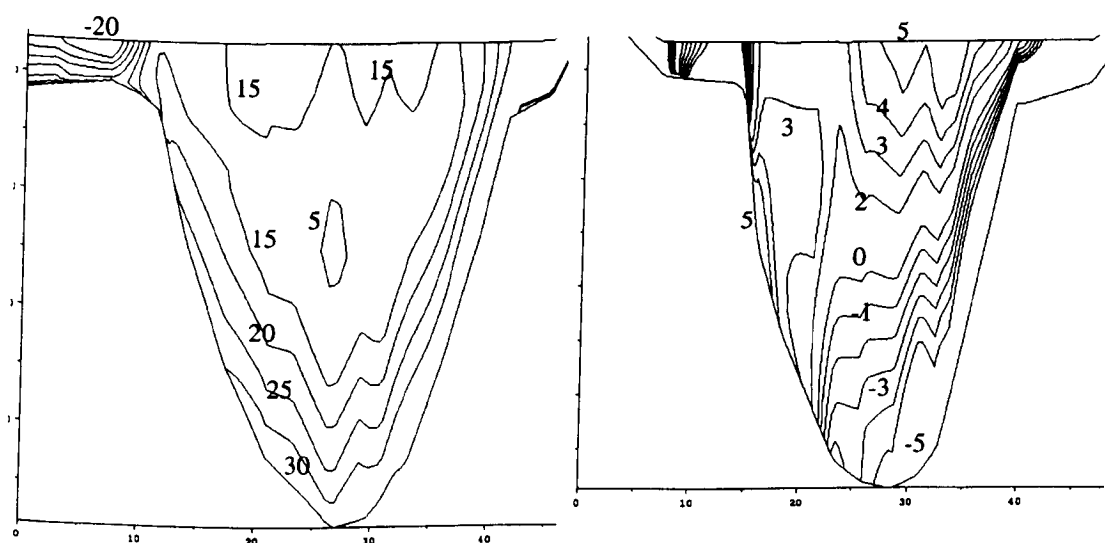
Cross-Section 4

**Fig. 6.67 – River Ribble TELEMAC Velocity Orientation (deg.) at Cross-Sections 1, 2, 3 and 4 ( $C = 38 \text{ m}^{1/2}/\text{s}$  on the flood plain,  $C = 55 \text{ m}^{1/2}/\text{s}$  in the main Channel, mixing-length model)**



Cross-Section 5

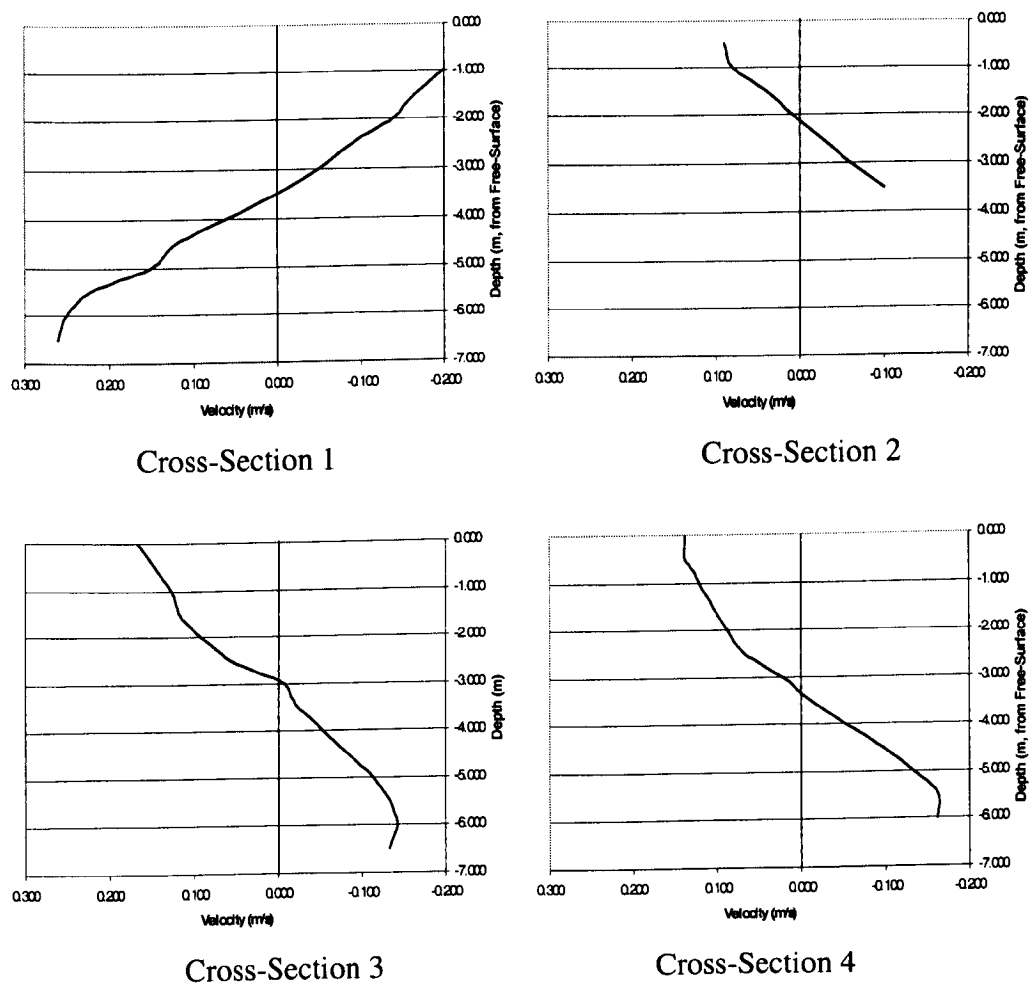
Cross-Section 6



Cross-Section 7

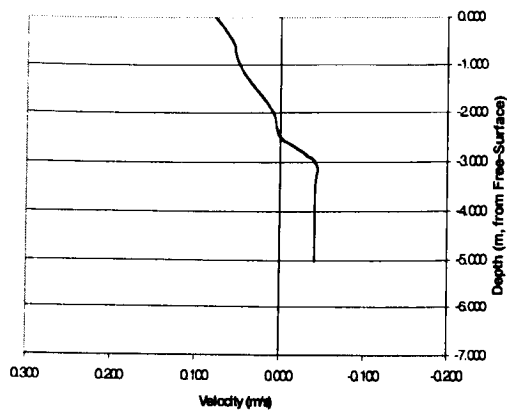
Cross-Section 8

**Fig. 6.68 – River Ribble TELEMAC Velocity Orientation (deg.) at Cross-Sections 5, 6, 7 and 8 ( $C = 38 \text{ m}^{1/2}/\text{s}$  on the flood plain,  $C = 55 \text{ m}^{1/2}/\text{s}$  in the main Channel, mixing-length model)**

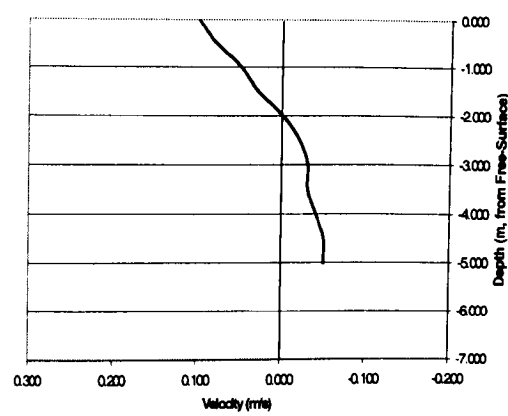


**Fig. 6.69 – River Ribble TELEMAC Model: Recirculation at Cross-Sections 1 to 4**

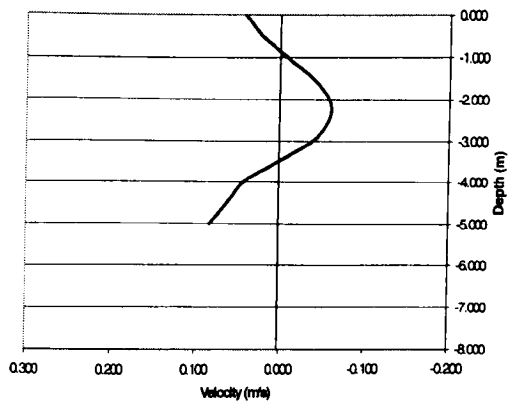




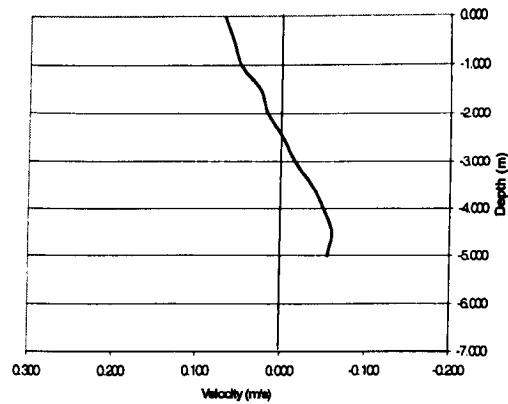
Cross-Section 5



Cross-Section 6

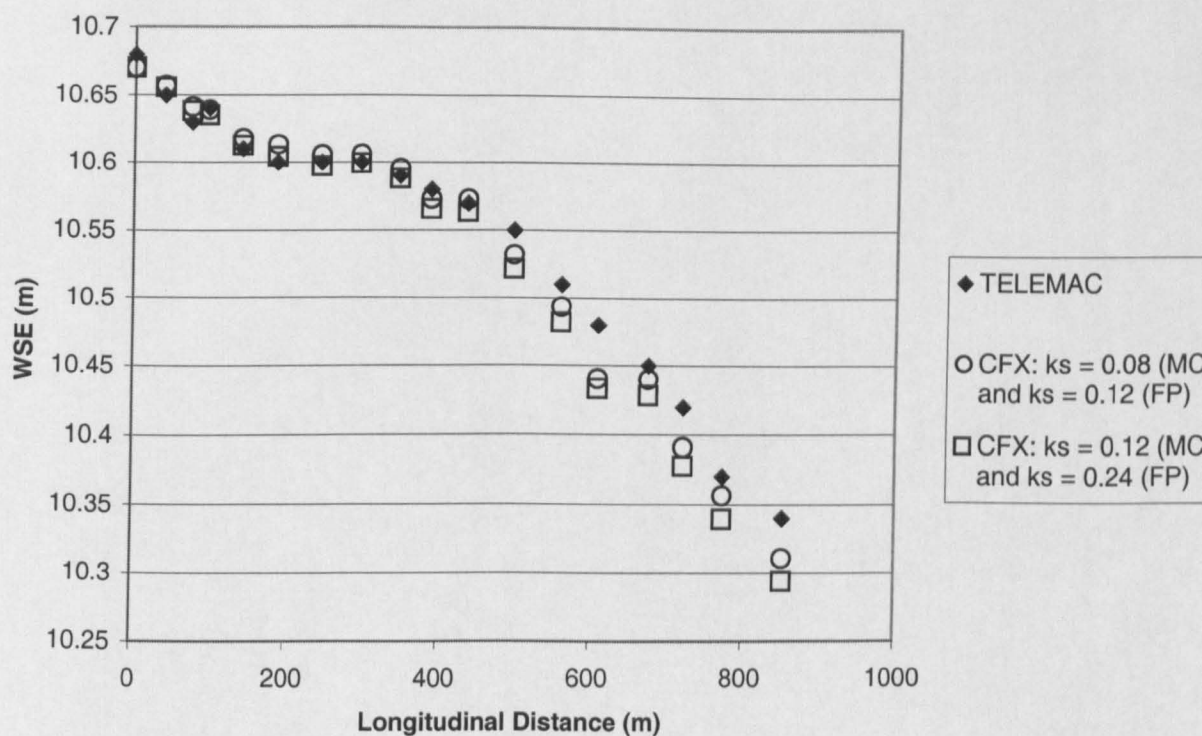


Cross-Section 7



Cross-Section 8

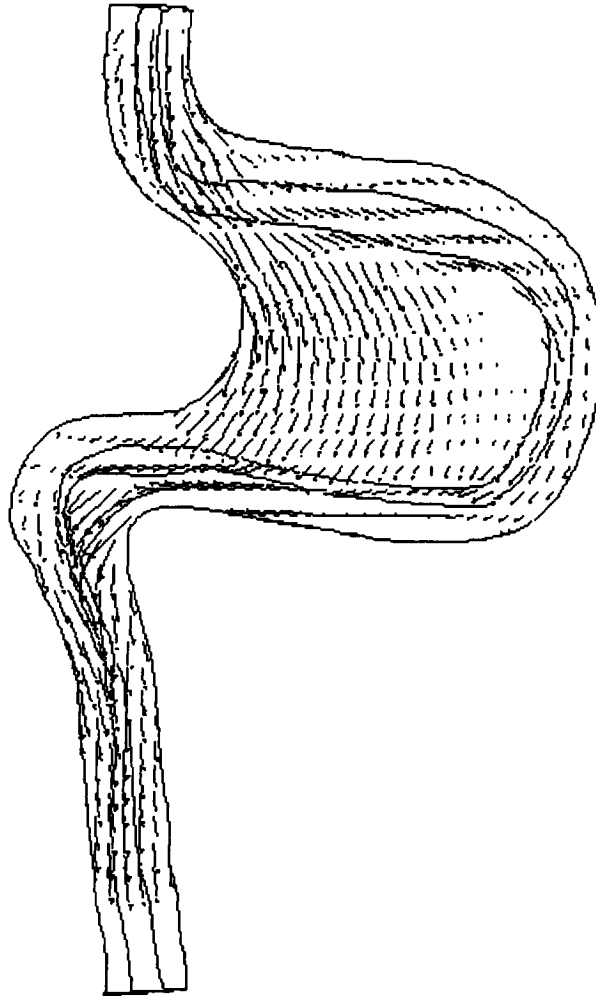
**Fig. 6.70 – River Ribble TELEMAC Model: Recirculation at Cross-Sections 5 to 8**



**Fig. 6.71 – River Ribble: Comparison between Water Surface Elevation Predicted by TELEMAC and CFX (98 m<sup>3</sup>/s)**

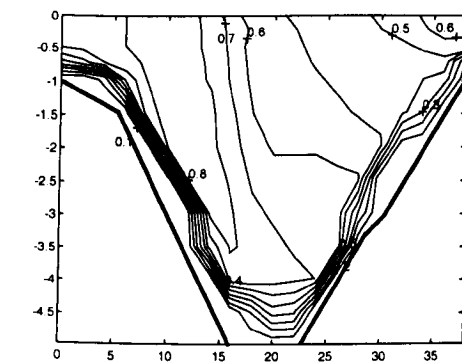


**Fig. 6.72 – Calculated CFX Pressure Field (Pa) on the Lid**

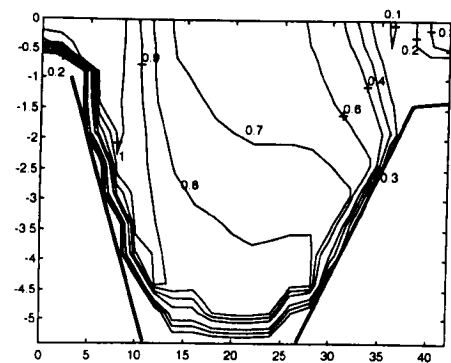


**Fig. 6.73 – River Ribble CFX Velocity Vectors close to the Free Surface for a Flow of  $98 \text{ m}^3/\text{s}$  ( $k_s = 0.08 \text{ m}$  in the main channel,  $k_s = 0.12 \text{ m}$  on the floodplain)**

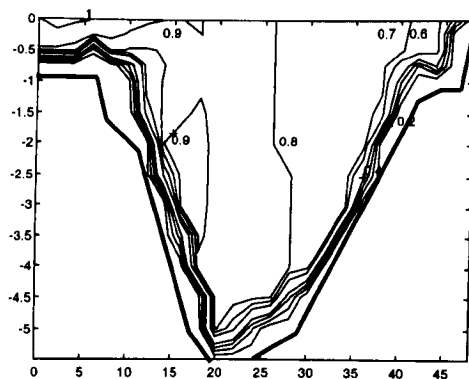




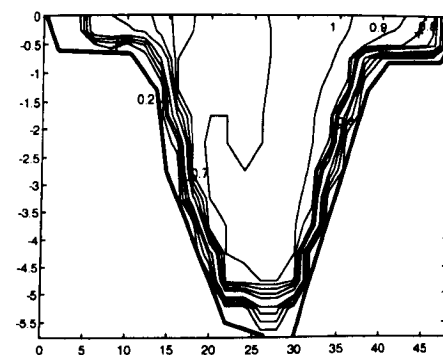
Cross-Section 5



Cross-Section 6

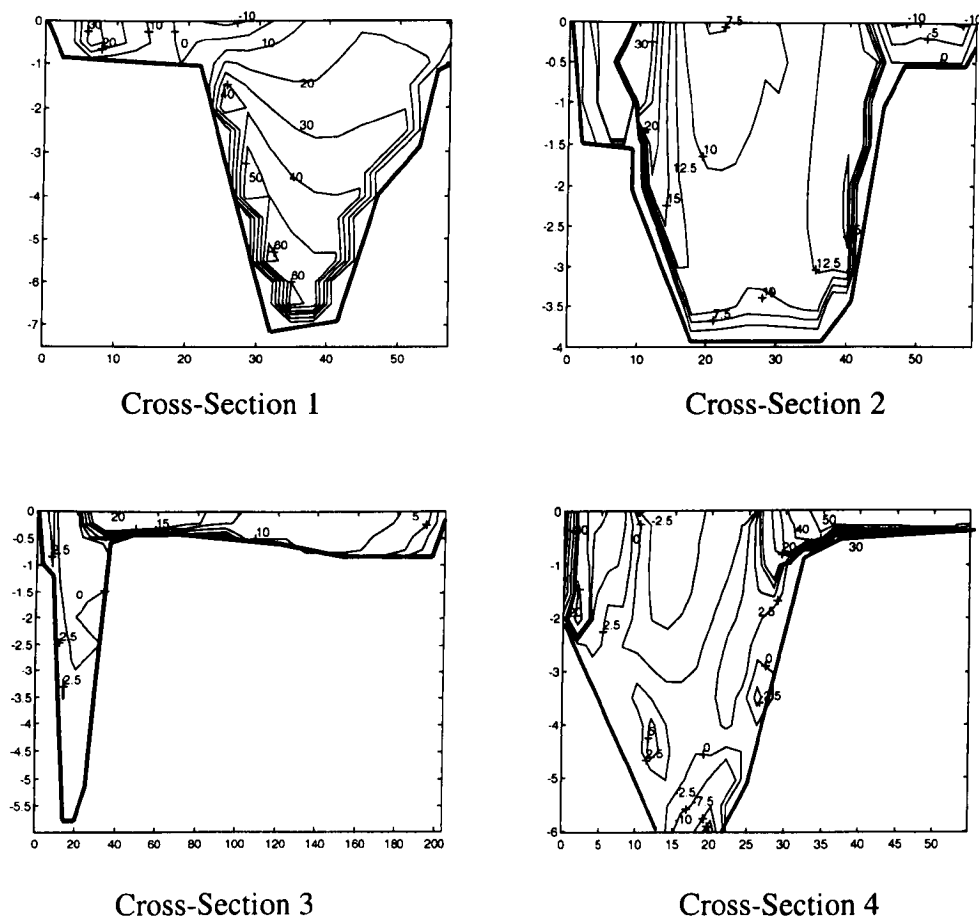


Cross-Section 7

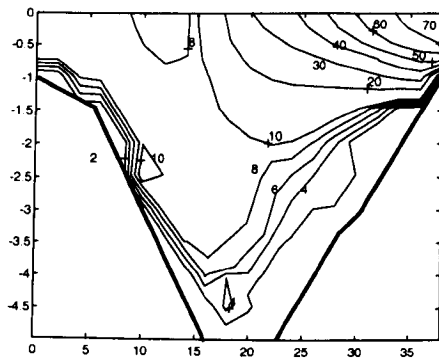


Cross-Section 8

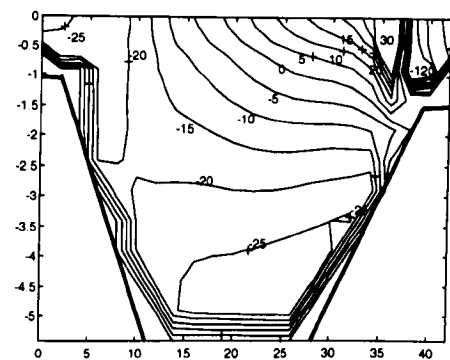
**Fig. 6.75 – River Ribble CFX Velocity Profile (m/s) at Cross-Sections 5, 6, 7 and 8**  
**( $k_s = 0.12$  m on the flood plain,  $k_s = 0.08$  m in the main channel,**  
**mesh R-1,  $k-\varepsilon$  model)**



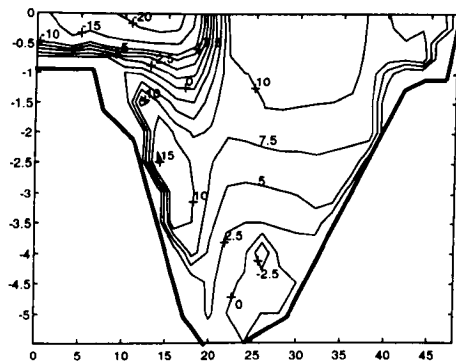
**Fig. 6.76 – River Ribble CFX Velocity Orientation (deg.) at Cross-Sections 1, 2, 3 and 4 ( $k_s = 0.12$  m on the flood plain,  $k_s = 0.08$  m in the main channel, mesh R-1,  $k$ - $\epsilon$  model)**



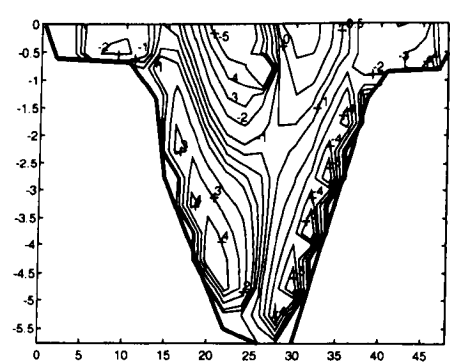
Cross-Section 5



Cross-Section 6

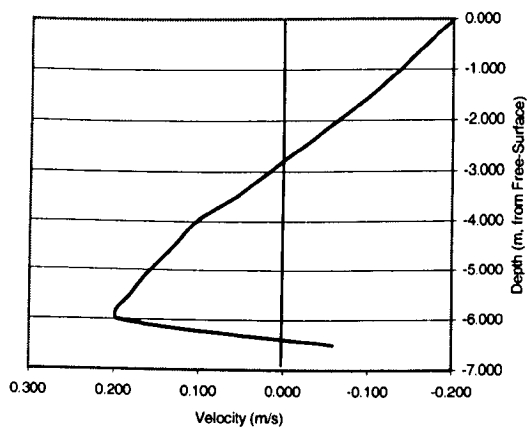


Cross-Section 7

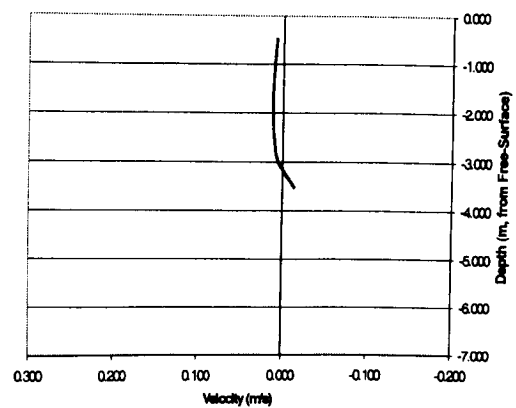


Cross-Section 8

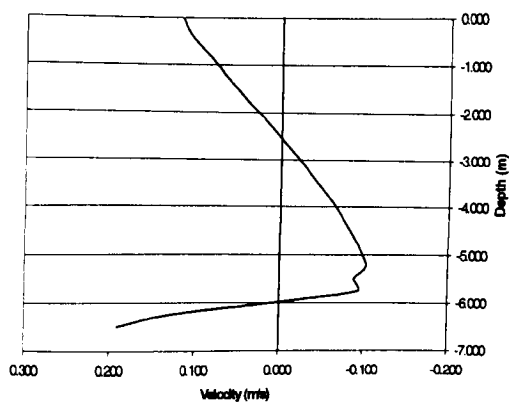
**Fig. 6.77 – River Ribble CFX Velocity Orientation (deg.) at Cross-Sections 5, 6, 7 and 8 ( $k_s = 0.12$  m on the flood plain,  $k_s = 0.08$  m in the main channel, mesh R-1,  $k-\varepsilon$  model)**



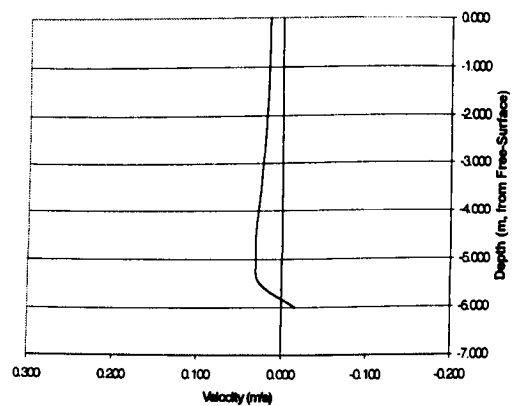
Cross-Section 1



Cross-Section 2



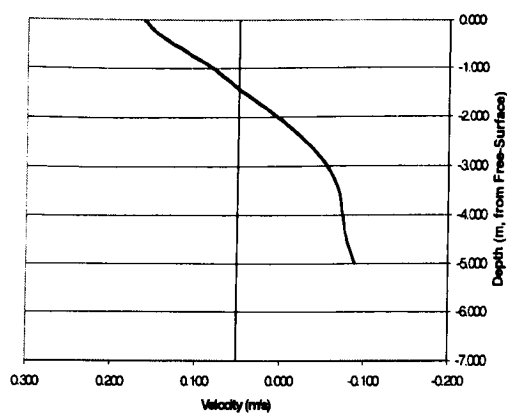
Cross-Section 3



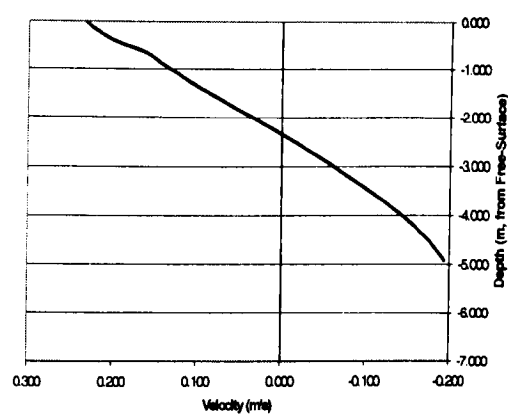
Cross-Section 4

**Fig. 6.78 – River Ribble CFX Model: Recirculation (m/s)  
at Sections 5, 6 and 7**

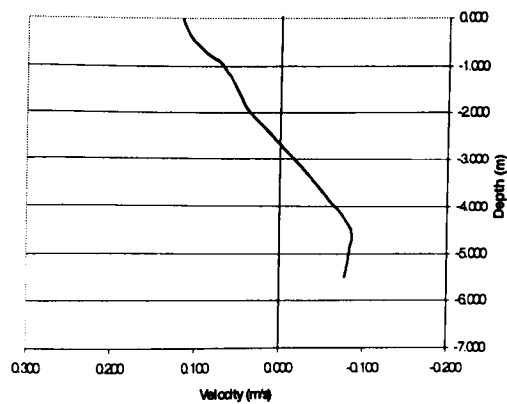




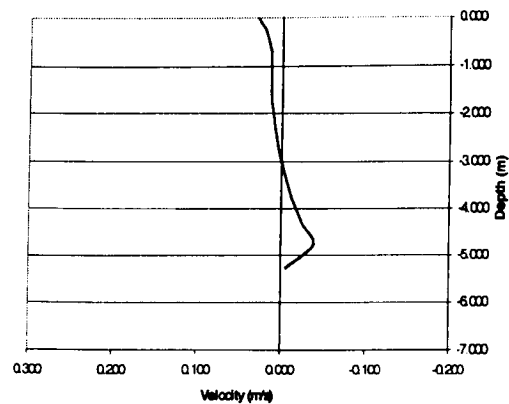
Cross-Section 5



Cross-Section 6

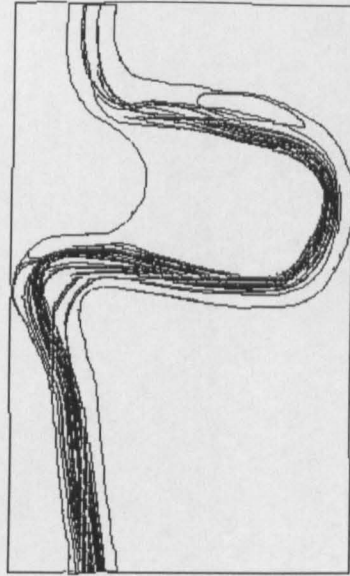


Cross-Section 7

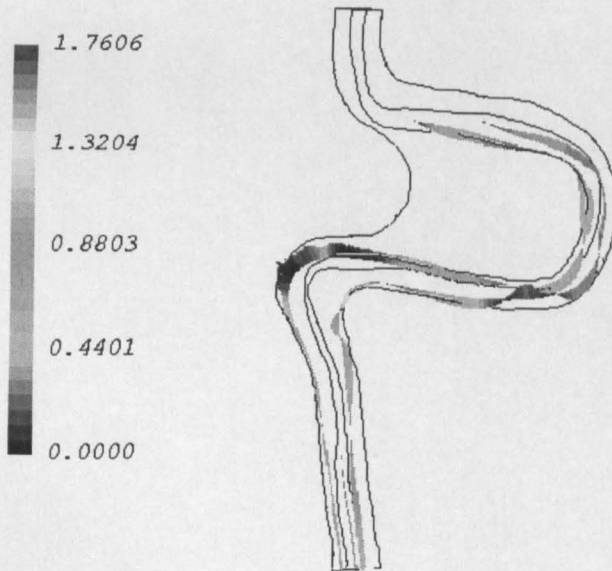


Cross-Section 8

**Fig. 6.79 – River Ribble CFX Model: Recirculation (m/s)  
at Sections 5, 6, 7 and 8**

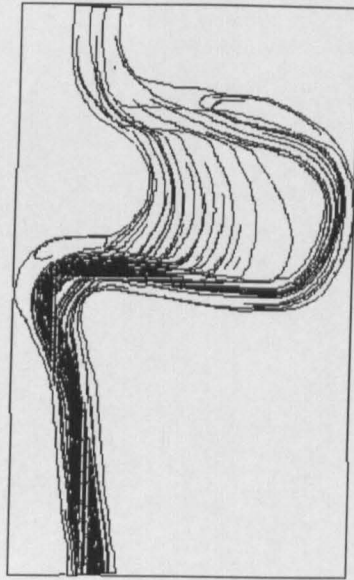


(a)

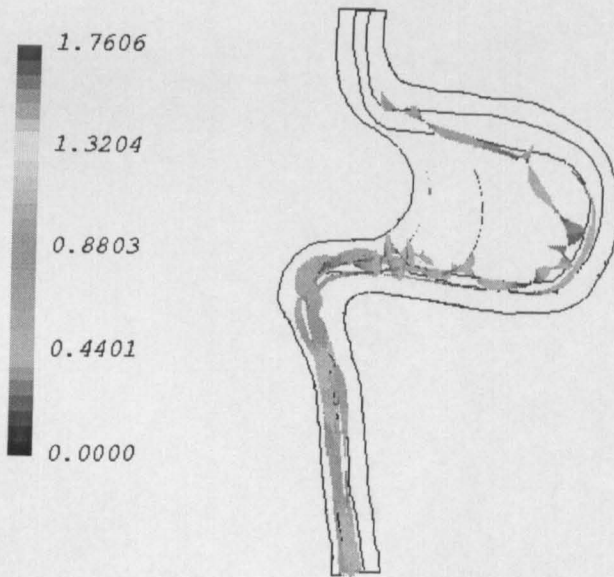


(b)

**Fig. 6.80 – CFX Numerical Tracer Release at Elevation 7.0 m in the Ribble :**  
**(a) Tracer Route**  
**(b) Rotational effects and Velocity**

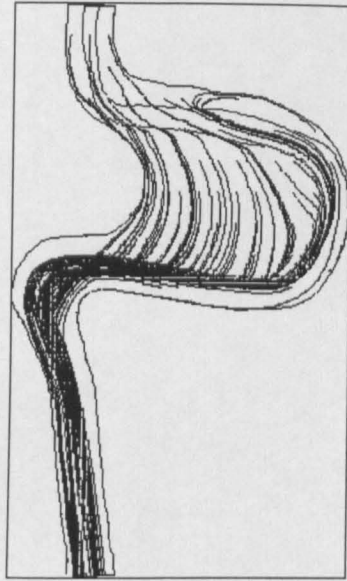


(a)

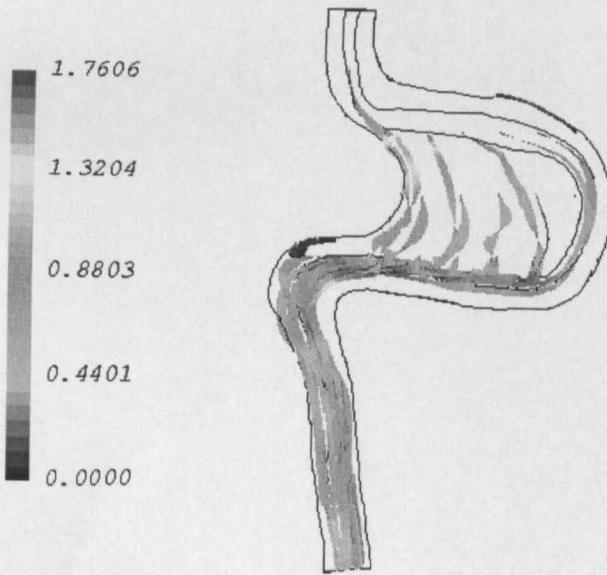


(b)

**Fig. 6.81 – CFX Numerical Tracer Release at Elevation 10.0 m in the Ribble:**  
**(a) Tracer Route**  
**(b) Rotational effects and Velocity**

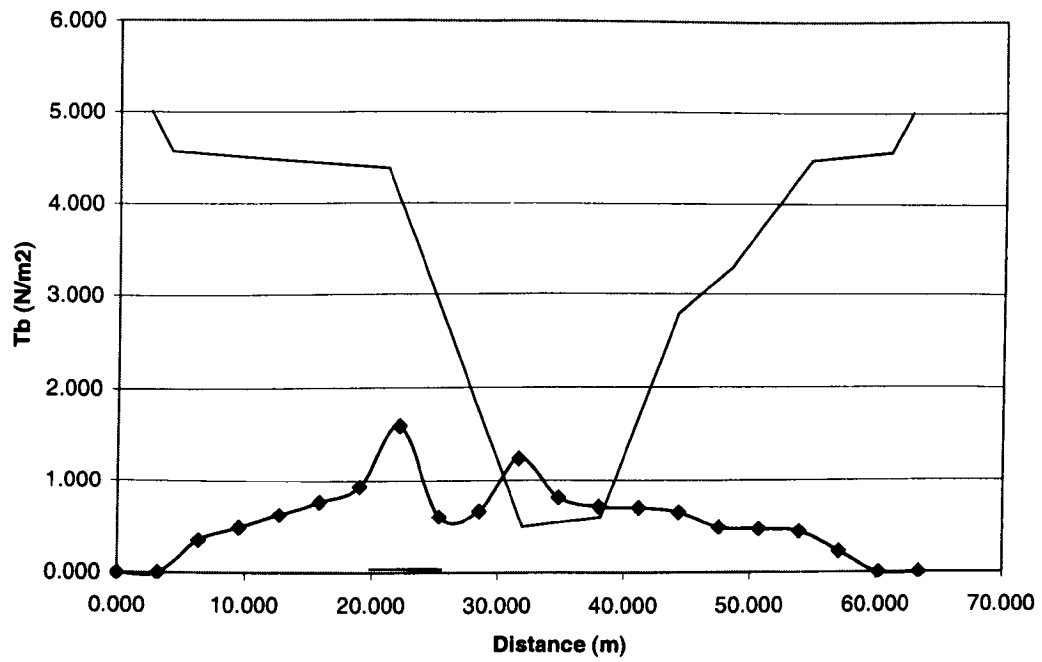


(a)

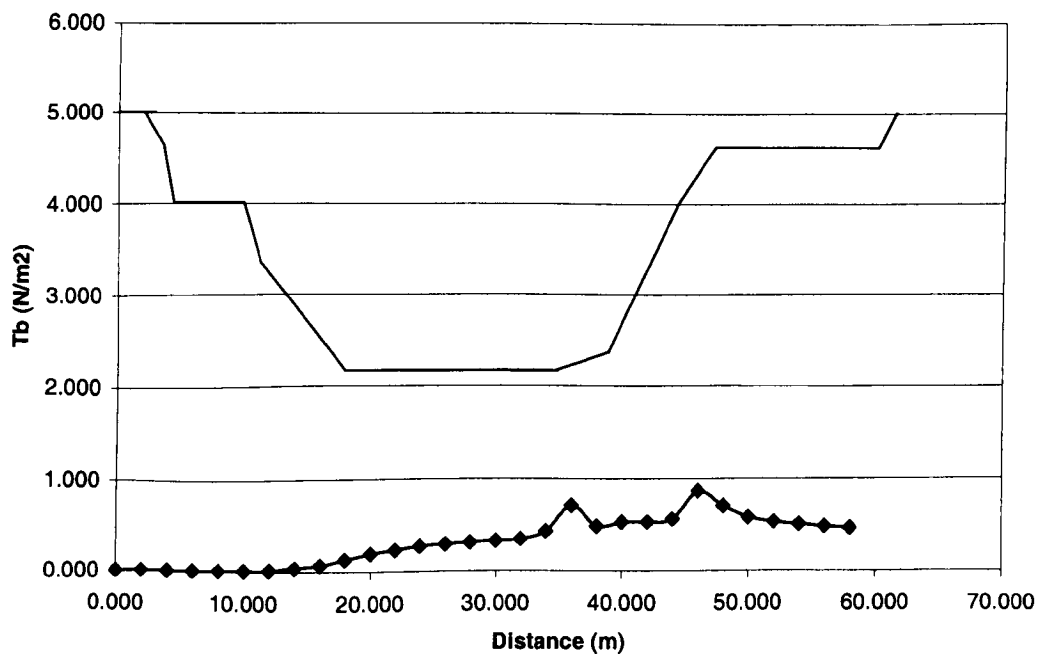


(b)

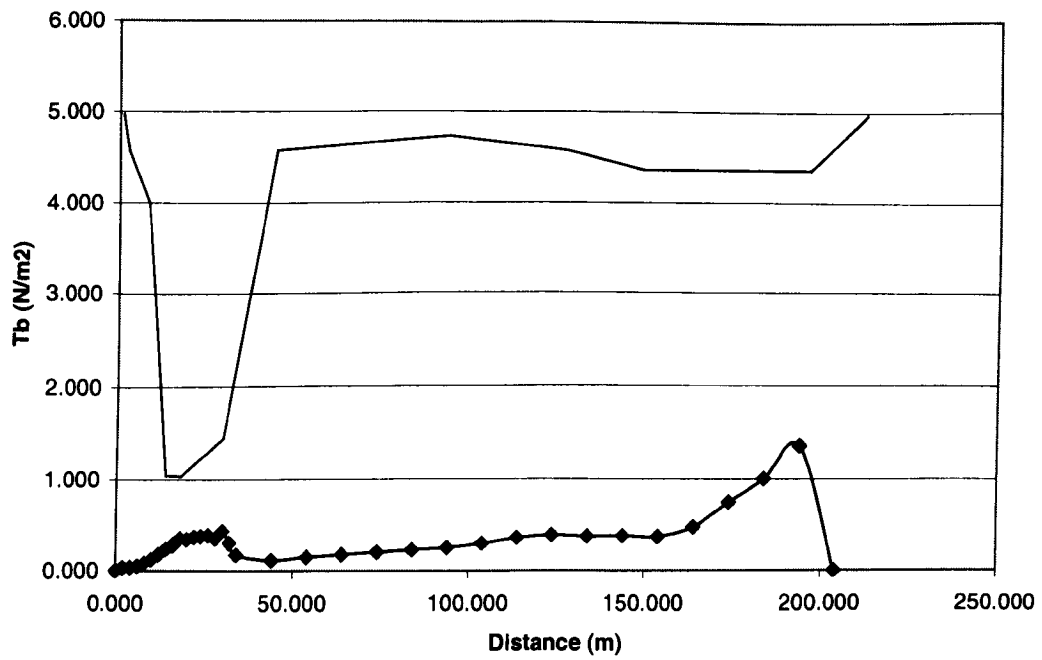
**Fig. 6.82 – CFX Numerical Tracer Release at Elevation 10.5 m in the Ribble:**  
**(a) Tracer Route**  
**(b) Rotational effects and Velocity**



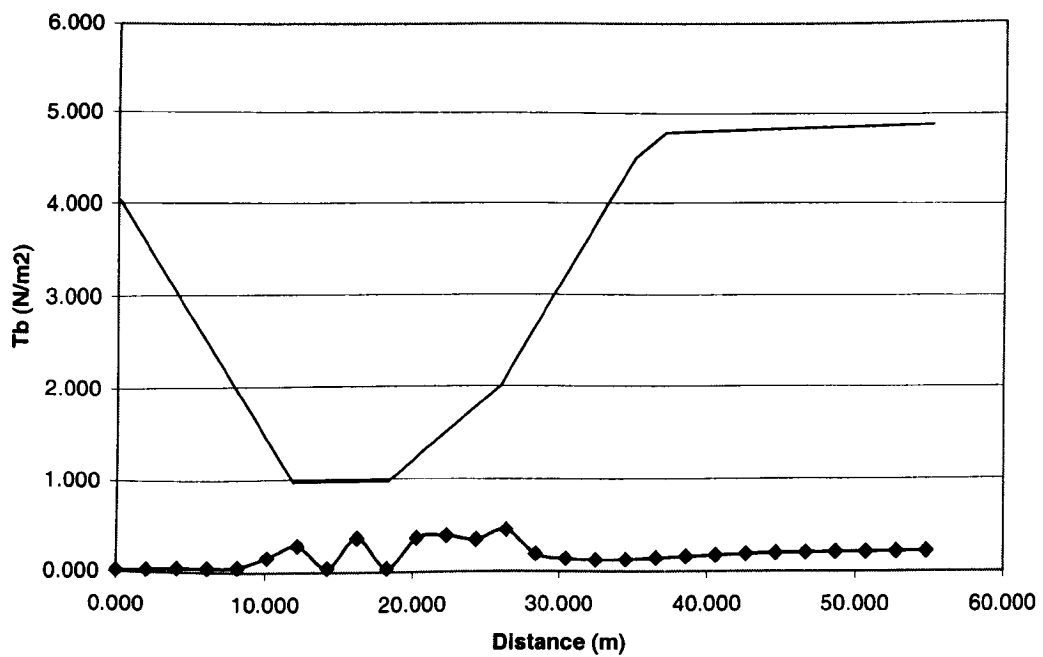
**Fig. 6.83 – Calculated Bed Shear Stresses at Section 1 from River Ribble Model ( $k-\varepsilon$  model)**



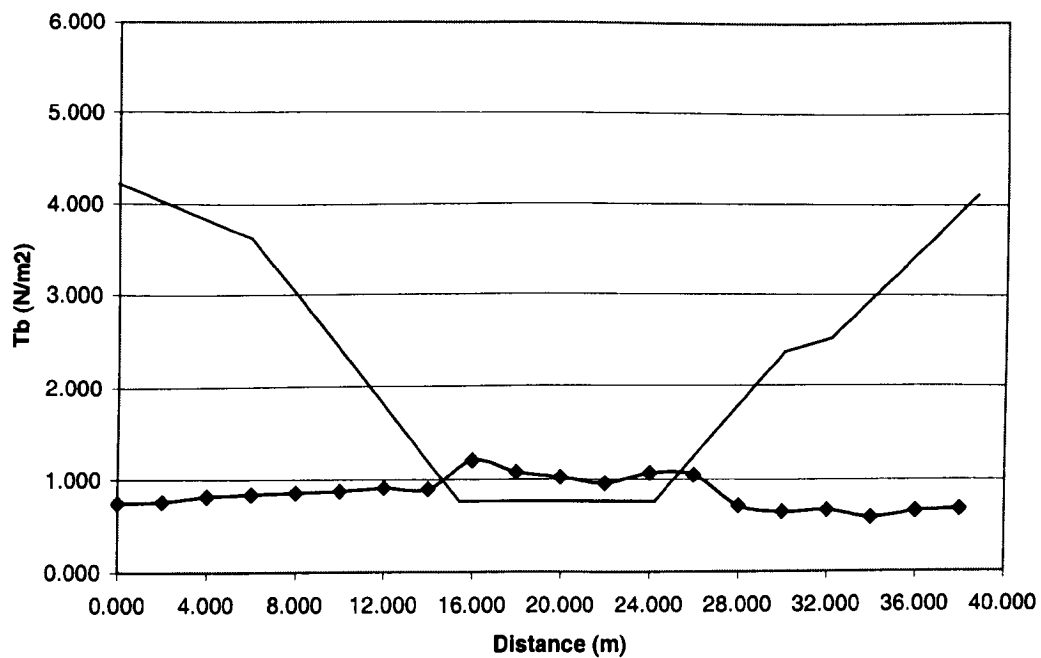
**Fig. 6.84 – Calculated Bed Shear Stresses at Section 2 from River Ribble Model ( $k-\varepsilon$  model)**



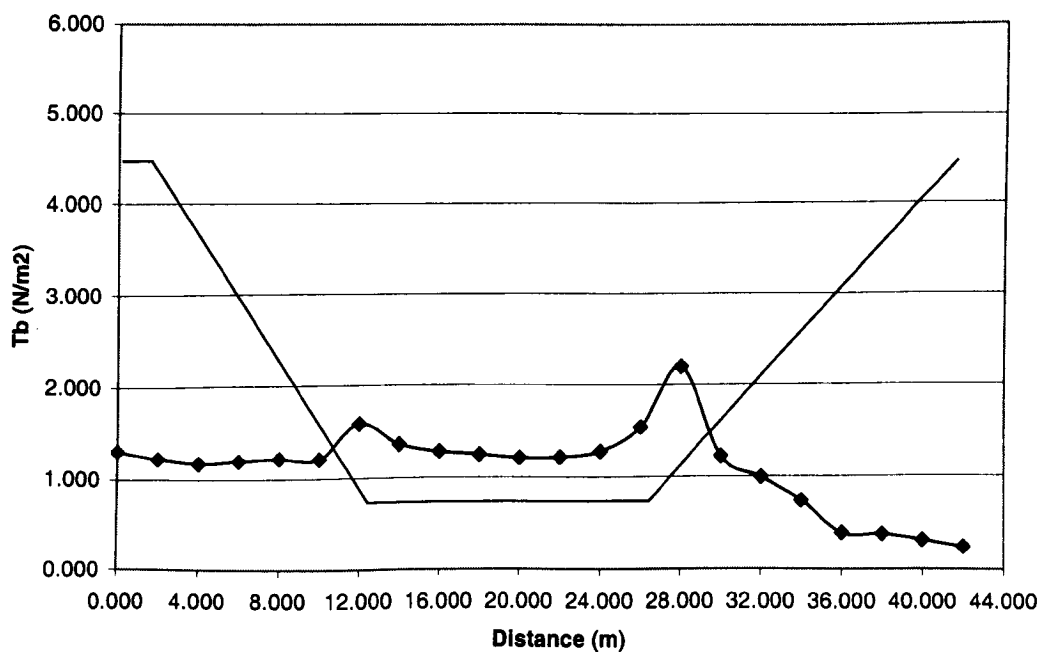
**Fig. 6.85 – Calculated Bed Shear Stresses at Section 3 from River Ribble Model ( $k-\epsilon$  model)**



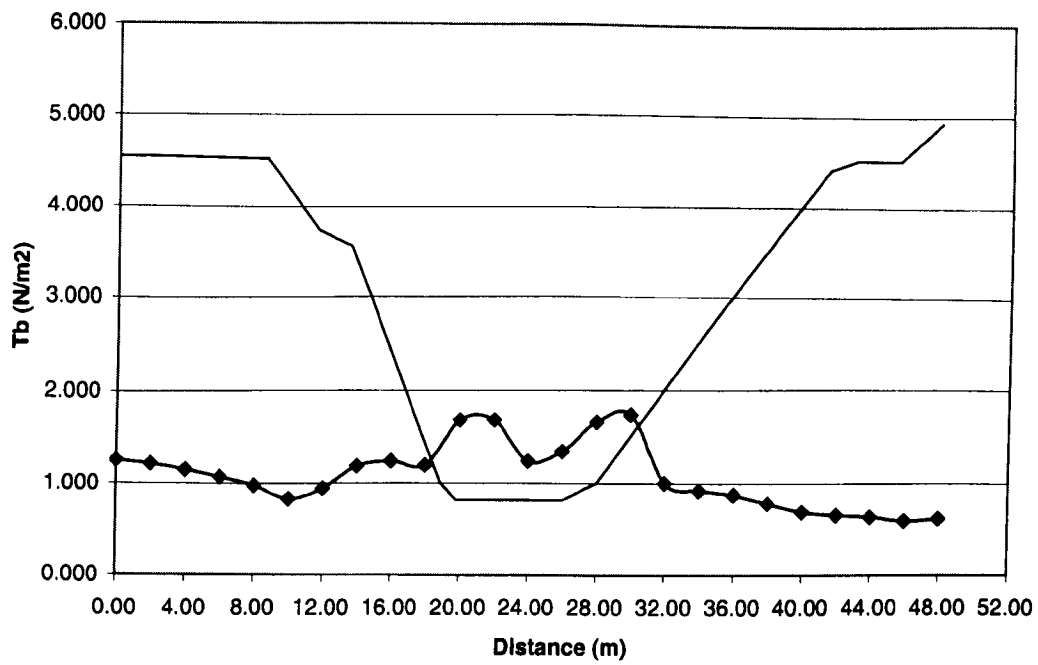
**Fig. 6.86 – Calculated Bed Shear Stresses at Section 4 from River Ribble Model ( $k-\epsilon$  model)**



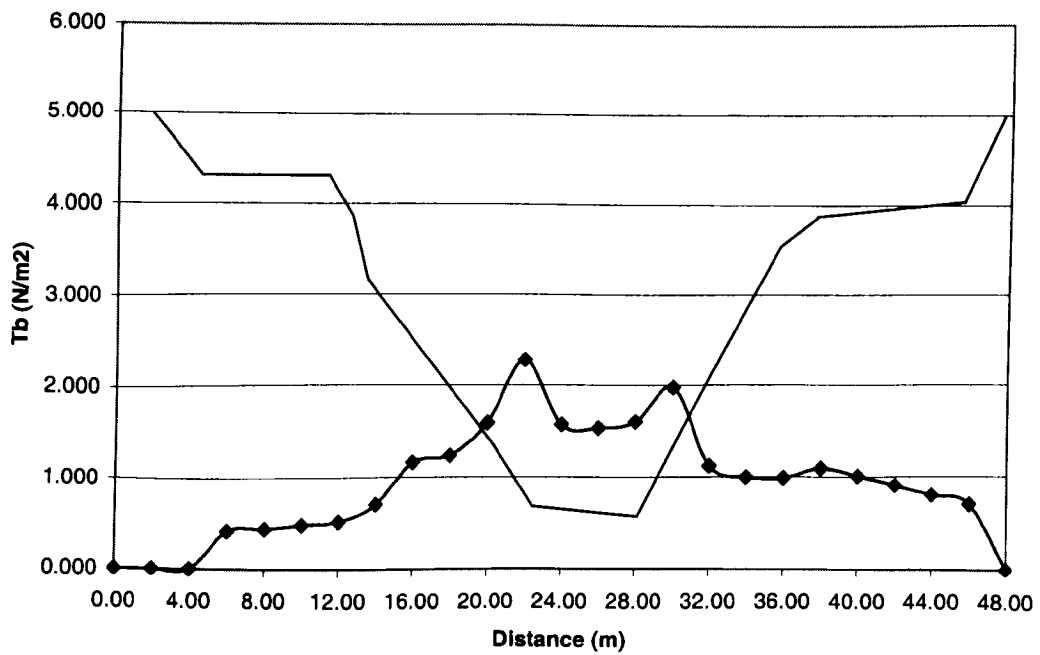
**Fig. 6.87 – Calculated Bed Shear Stresses at Section 5 from River Ribble Model ( $k$ - $\epsilon$  model)**



**Fig. 6.88 – Calculated Bed Shear Stresses at Section 6 from River Ribble Model ( $k$ - $\epsilon$  model)**

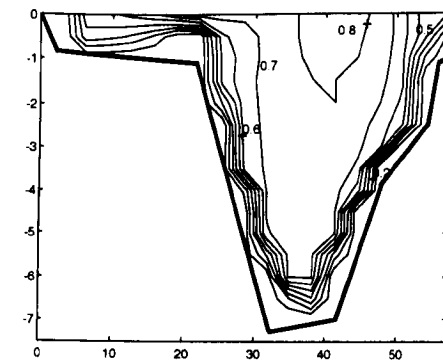


**Fig. 6.89 – Calculated Bed Shear Stresses at Section 7 from River Ribble Model ( $k$ - $\epsilon$  model)**

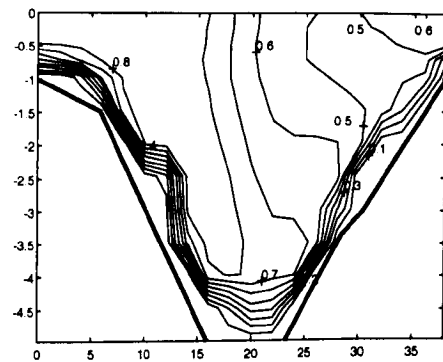


**Fig. 6.90 – Calculated Bed Shear Stresses at Section 8 from River Ribble Model ( $k$ - $\epsilon$  model)**

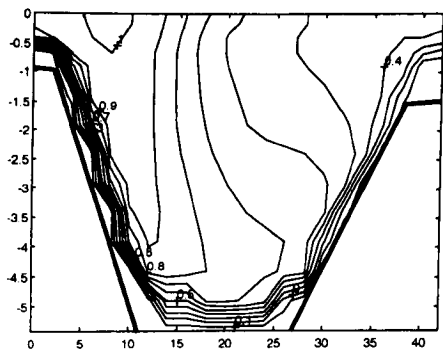




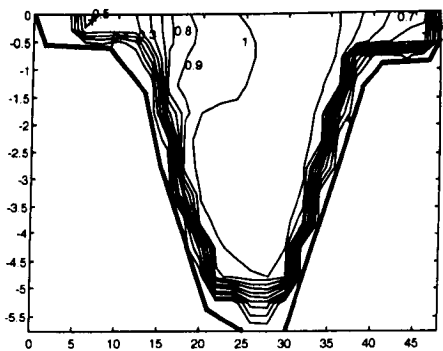
Cross-Section 1



Cross-Section 5



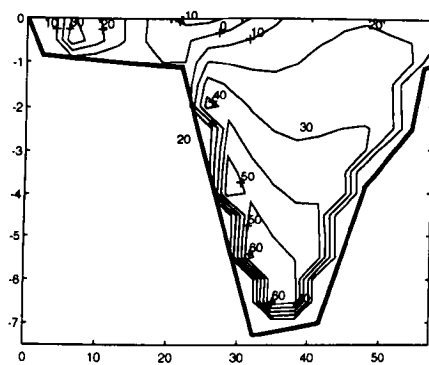
Cross-Section 6



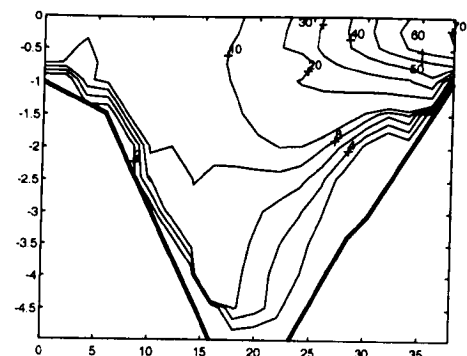
Cross-Section 8

**Fig. 6.91 – River Ribble CFX Velocity Profile (m/s) at Cross-Sections 1, 5, 6 and 8**  
**( $k_s = 0.12$  m on the flood plain,  $k_s = 0.08$  m in the main channel,**  
**mesh R-1, RSM)**

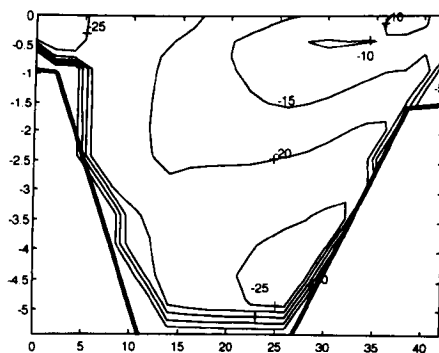




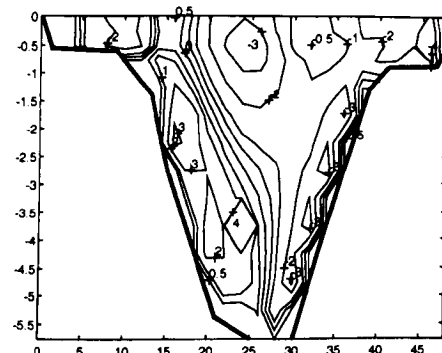
Cross-Section 1



Cross-Section 5



Cross-Section 6



Cross-Section 8

**Fig. 6.92 – River Ribble CFX Velocity Orientation (deg.) at Cross-Sections 1, 5, 6 and 8 ( $k_s = 0.12$  m on the flood plain,  $k_s = 0.08$  m in the main channel, mesh R-1, RSM)**